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Terrain Characterization for Modeling RF Propagation

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Terrain Characterization for Modeling RF Propagation

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This project was conducted in collaboration with the Institute for Telecommunication Sciences (ITS), the research and engineering laboratory of the National Telecommunications and Information Administration (NTIA), an agency of the U.S. Department of Commerce.

ITS and its predecessor organizations have been developing and improving radio frequency (RF) propagation models for more than a century. These mathematical algorithms predict the behavior of radio waves, and are an essential enabler for spectrum sharing.

ITS developed and publishes the Irregular Terrain Model (ITM), currently the most widely used RF propagation model in the world. Increased demand for spectrum, advances in wireless communications technology, and the tremendous growth in everyday spectrum usage are driving research and testing to improve the accuracy of existing propagation models.

ITS has been working to better understand how to factor in the effects of clutter (man-made structures and vegetation) when analyzing and predicting the behavior of radio waves and has observed that disparate elevation data sources can have a significant impact on model predictions.

Past IDA efforts constructing synthetic environments for modeling and simulation and ongoing work with National Geospatial-Intelligence Agency provide IDA research staff members with unique insights in characterizing legacy, contemporary and emerging geospatial data sources representing terrain, man-made structures and vegetation.

Similarly, IDA research staff members have extensive experience in sensor and communications modeling. This effort capitalized on both areas of expertise.

Approach

- To initiate collaboration with this technical community, several versions of a Digital Elevation Model tutorial (see Appendix) were presented to technical staff:
 - Institute for Telecommunication Sciences (ITS) on April 20, 2017 and August 22, 2017
 - Propagation Working Group, Spectrum Sharing Test & Demonstration (SST&D) Program, Defense Spectrum Organization (DSO) on September 12, 2017
- Valuable feedback and insight was provided by both organizations.
- ITS and DSO are collaborating to support national policy decisions for RF spectrum allocation and management between civil wireless industry and DoD
- Radio Frequency (RF) propagation modeling is critical to this work:
 - ITS relies on the Irregular Terrain Model (ITM)
 - DSO and contractor base use the Terrain Integrated Rough Earth Model (TIREM)
 - Industry utilizes both models as well as other commercial and proprietary models
- Disparities between model predictions and field measurements are the norm



2

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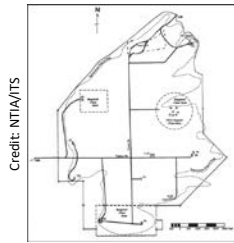
- ITS relies on the Irregular Terrain Model (ITM);
- DSO and contractor base use the Terrain Integrated Rough Earth Model (TIREM); and
- Industry utilizes both models as well as other commercial and proprietary models.

Disparities between the model predictions and field measurements are the norm. Digital terrain models (DEM) are a critical components for all RF propagation models.

Research staff at ITS had observed variance in analytical result using different DEMs.

Technical staff at ITS, DSO, and the DSO contractor base were using various DEMs without a deep understanding of their characteristics.

Table Mountain Study



NTIA/ITS Research Site at Table Mountain
(Longmont, Colorado)

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- ITS furnished a current MATLAB version of ITM for use at IDA
- ITS provided 3.5 GHz field measurements collected for a transmitter in Boulder, Colorado and a mobile receiver traversing the Table Mountain research site near Longmont, Colorado (~ 20 km path length)
- To investigate potential variability depending on terrain data, multiple ITM runs were made estimates of 3.5 GHz loss over the path from Boulder to Table Mountain to using four different DEM for comparison to the ITS field measurements

3

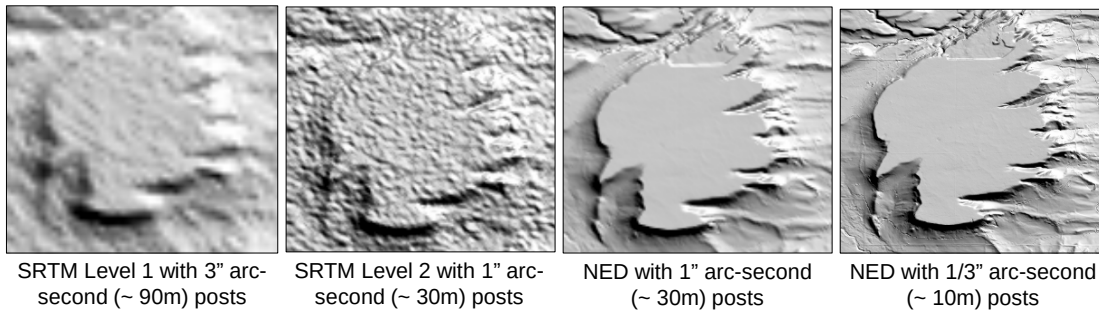
At the start of this CRP, it was hypothesized that differences in elevation data were contributing to anomalous propagation loss estimates that ITS researchers had encountered using their ITM propagation loss model. Since our contact with ITS was limited by the modest scale of this project, the effort focused on work that could be performed at IDA.

ITS furnished a current MATLAB version of ITM for use at IDA. ITM models radio propagation for frequencies between 20 MHz and 20 GHz (Longley-Rice).

ITS also provided 3.5 GHz field measurements collected for a transmitter at the ITS campus in Boulder and a mobile receiver traversing the Table Mountain research site near Longmont, Colorado (~ 20 km path length).

To investigate potential variability depending on terrain data, IDA assessed ITM estimates of 3.5 GHz loss over the path from Boulder to Table Mountain using four different DEM for comparison to the 3.5 GHz field measurements.

Selected DEM Coverage over Table Mountain



- Shuttle Radar Topographic Mission (SRTM) elevation data derived from Interferometric Synthetic Aperture Radar (IFSAR) shows anomalous “lumps” in terrain surface
- National Elevation Data (NED) was derived from airborne Light Detection and Ranging (LIDAR) where laser scanner “point clouds” were processed to generate 1 meter, 1/3 arc-second, and 1 arc-second DEM

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4

For Shuttle Radar Topographic Mission (SRTM) in 2000, the space shuttle Endeavor carried a synthetic aperture radar (SAR) transmit/receiver antenna in the shuttle bay and an extensible 60 meter boom used to deploy a second antenna in orbit. This enabled interferometric processing (IFSAR) to extract terrain elevations. Near-global coverage was processed and finished to generate SRTM Level 1 (3 arc-second or ~ 90 meter post spacing) and SRTM Level 2 (1 arc-second or ~ 30 meter post spacing) products.

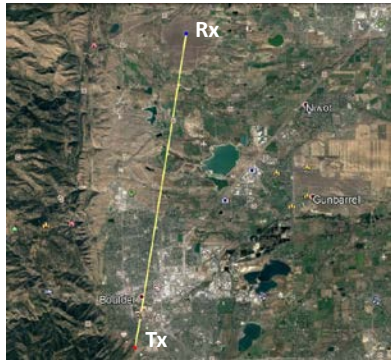
SRTM was a joint project between the National Aeronautic and Space Agency (NASA) and the National Imagery and Mapping Agency (NIMA, now NGA).

The key characteristic of IFSAR DEM is “lumpiness” in the extracted terrain surface due to inherent noise sources. SRTM “lumps” range from approximately 3 to 5 meters in height with irregular spacing on the order of 100 meters. While these artifacts are particularly evident in SRTM Level 2 data, they are present in SRTM Level 1 data as well although significantly reduced by smoothing.

For the coterminous United States, the U.S. Geological Survey (USGS) has undertaken a national campaign to collect elevation data using airborne Light Detection and Ranging (LIDAR) scanners. Table Mountain lies in a region where LIDAR “point clouds” were collected and processed to generate 1 meter, 1/3 arc-second, and 1 arc-second DEM as part of the National Elevation Data (NED) program

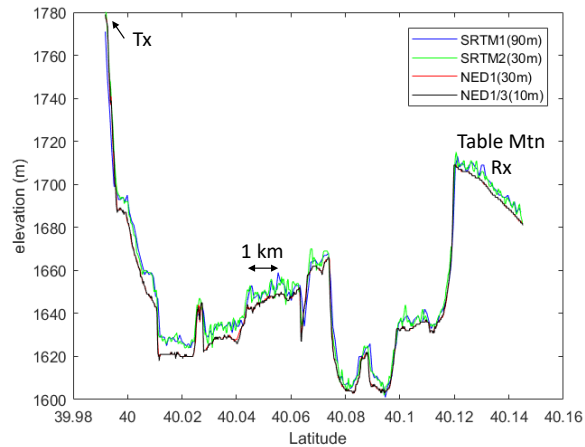
Both the 1 arc-second (~ 30 meter post spacing) and 1/3 arc-second (~ 10 meter post spacing) NED reflect the relatively smooth surface of the Table Mountain mesa. The higher resolution captured at 1 arc-second is evident in the increased detail seen in the gullies surrounding the Table Mountain mesa.

Terrain Profiles for Table Mountain Field Measurements



Path from the transmitter position (Tx) to northern-most receiver position (Rx) for the 3.5 GHz Table Mountain field measurements

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5

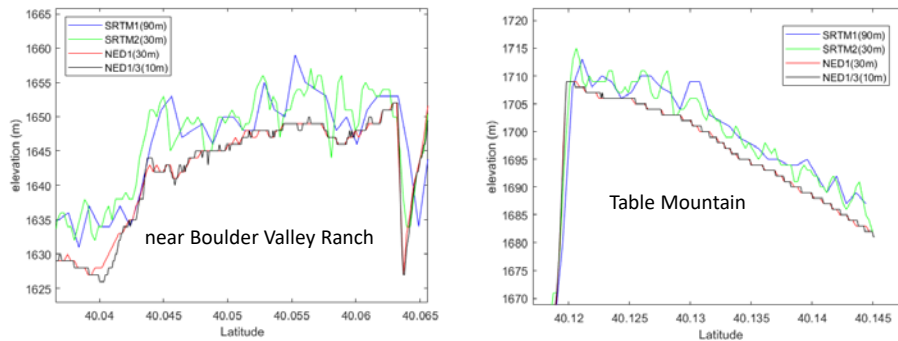
ITS measurements were made with a 3.5 GHz transmitter located at the ITS campus in Boulder, Colorado and a receiver mounted on a vehicle that drove across the Table Mountain plateau near Longmont, Colorado.

An overhead view of the roughly 20 kilometer RF link between the transmitter (Tx) and the receiver (Rx) is shown in the figure on the left.

Terrain profiles for the four DEMs are shown on the right where the X-axis plots the RF link path as a function of latitude in decimal degrees and the Y-axis plots elevation in meters.

Note that the SRTM profiles shows more short-scale undulations than the NED profiles reflecting IFSAR artifacts. Also, SRTM data tends to have a slightly higher average elevation as compared to NED.

Comparative Terrain Profiles



SRTM data has noticeable terrain undulations and higher elevations than NED



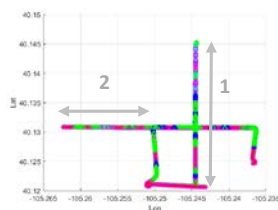
6

Larger-scale terrain profiles at two locations along the RF link are shown in the figures. These provide a more detailed view of the terrain profile differences discussed on the previous page.

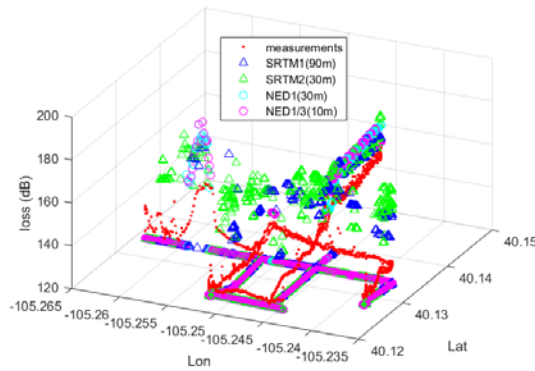
Correlation between SRTM Level 1 and SRTM Level 2 terrain is expected. Although they are different spatial resolutions, they are derived from the same IFSAR source.

Correlation between 1 arc-second and 1/3 arc-second NED is also expected since they are derived from the same LIDAR source.

Loss Measurements and Calculations



Plan view of full Rx path
on Table Mountain



Signal loss versus position

- 1,490 measurements were made on the Table Mountain mesa
- ITM model run with SRTM1, SRTM2, NED 1, NED 1/3 profile inputs
- Loss measurements and estimates available as a function of position
- Focus on gray paths (1 & 2) seen in plan view

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7

Loss measurements were made at 1,490 locations atop Table Mountain as shown in the plan view in the upper left figure.

ITM estimates can be compared to each field measurement as shown in the “Signal loss versus position” plot where the horizontal plane plots position in terms of longitude on the X-axis and latitude on the Y-axis (both decimal degrees) and signal loss (dB) is plotted on the Z-axis.

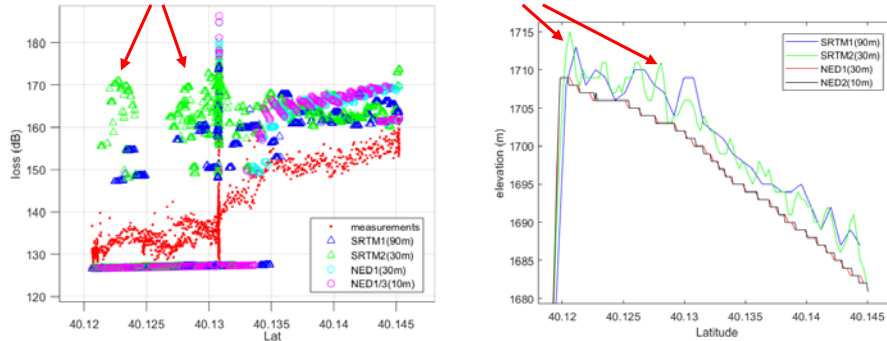
The lowest points in the plot are consistent with free-space loss and represent most of the ITM predictions for each DEM. The field measurements are shown by red dots. It can be seen that these approach free-space loss conditions, but usually exhibit more severe loss conditions.

Some of ITM predictions do show increased loss, but these predictions tend to have higher losses than the measurements.

To see these effects more clearly, we will now focus on the gray paths seen in the upper plot labelled “1” running from south to north and “2” running west to east.

Signal Loss versus Latitude

Features in predicted loss possibly due to SRTM terrain features?



- In the southern part of site, measured loss is a ~ few 10 db above free space
 - ITM mostly consistent with free space (under-predicts measured loss)
 - High-loss features predicted using SRTM (especially SRTM2), perhaps due to surface undulations
- In the northern part of site, ITM estimated loss exceeds measurements (over-predicts measured loss)

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8

Here, we consider south-to-north path across Table Mountain previously labelled “1”.

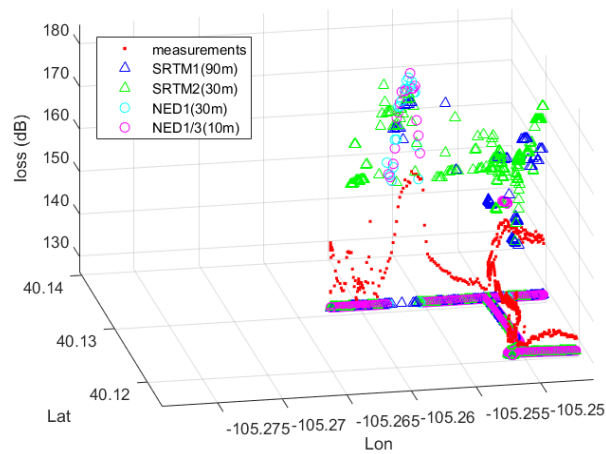
In the left plot, ITM signal loss predictions are compared to field measurements with latitude (decimal degrees) plotted on the X-axis and signal lost (dB) on the Y-axis.

On the southern part of the path, the field measured loss is a few to 10 dB above free space while the ITM predictions are largely consistent with free space.

In this case, ITM under-predicts the measured loss with the exception of ITM predictions using SRTM terrain, especially SRTM Level 2, where high-loss features are seen. This is likely due to surface undulations in SRTM terrain as seen in the right figure where the corresponding terrain profile is plotted with latitude (decimal degrees) on the X-axis and elevation (meters) on the Y-axis.

On the northern part of site, ITM estimated loss exceeds measurements (over-predicts measured loss) at each point.

Loss on West Slope



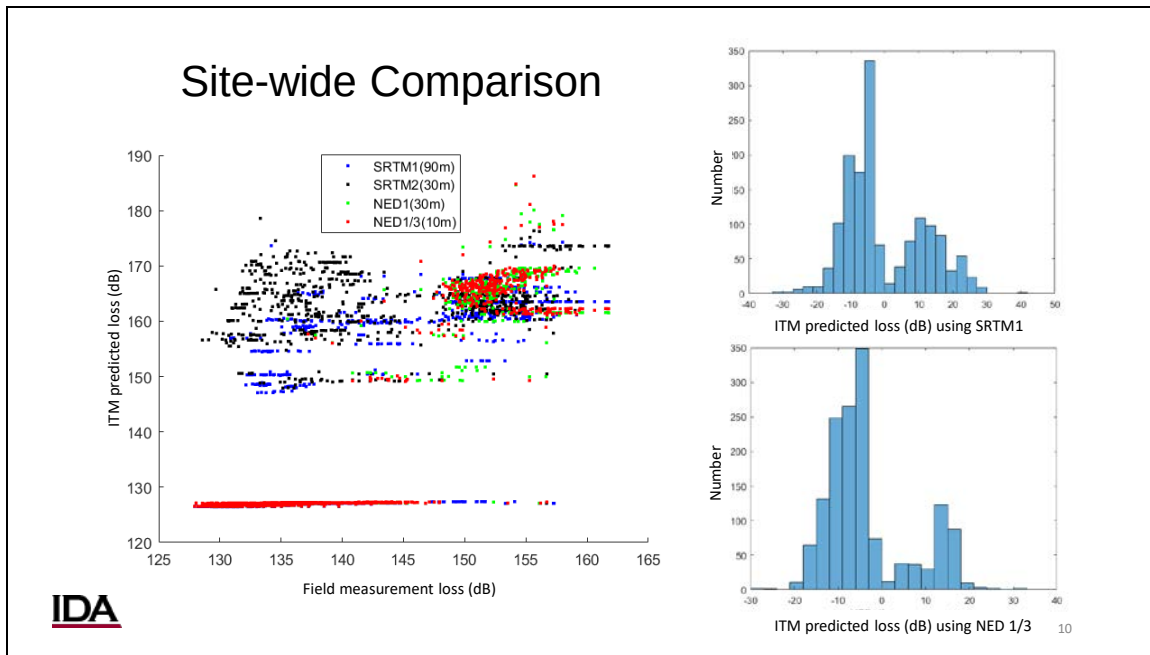
- High loss condition seen in measurements and models along road leading down off of the north slope
- Similar trend as before – high loss conditions overestimated by model

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9

On the west-to-east path previously labelled “2”, we focused on a downward slope on the western-most part of the path.

High loss conditions are seen in measurements and models along the road. In most cases however, ITM estimated losses that were consistent with free-space. As before, the free-space loss predictions underestimated the actual loss while the high loss conditions were overestimated by model.



We performed a site-wide comparison for all 1,490 locations where field measurements were taken.

On the left, field measured signal loss (dB) is plotted on the X-axis with ITM predicted loss on the Y-axis. We see the basic bifurcation alluded to above clearly in this plot:

- ITM either predicts free-space loss which is an under-prediction of the actual loss, or
- ITM predicts a loss above free space conditions that are over-predictions of loss when compared to the actual measurements.

The two histograms on the right compiled for ITM loss estimates using SRTM Level 1 (~ 90 meter posts) and ITM loss estimates using NED 1/3 arc-second (~ 10 meter posts) illustrate this as well.

Conclusions and Future Thoughts

- Additional models and/or elevation maps could be run over the coming month if helpful
- NED decimal meters (floating point) vs. meters (integer)
- In future, measurements taken at multiple frequencies would help to determine where dominant multiple scattering occurs, and this could help inform model improvements
- HSIP Urban
- In addition to terrain, land cover databases may be helpful in accurately modeling multiple scattering in future models
- Follow-on work under Task AK-2-3475, Communications and Networking Technologies, for the Deputy Assistant Secretary of Defense, Research



11

This CRP project had two related objectives: (a) to gain insight into current practice in terrain modeling to predict RF propagation, and (b) to identify opportunities to exploit contemporary geo-spatial data sources to advance the state-of-the-art in RF propagation modeling.

Current practice for RF propagation modeling in the coterminous United States has been over-reliant on use of SRTM terrain with inherent IFSAR anomalies when higher fidelity and higher resolution data is available from USGS NED. NED has the additional benefit of representing elevation in decimal meters (floating point) rather than integer meters. Technical staff at ITS and DSO have been made aware of this opportunity.

In future, field measurements taken at multiple frequencies would help to determine where dominant multiple scattering occurs, and this could help inform model improvements

There is a keen interest within the RF propagation modeling for better “clutter” modeling particularly trees and buildings. Current efforts investigating use of the National Land Cover Database (NLCD) could be supplemented and refined through use of LIDAR-derived building and tree features collected under the Homeland Security Infrastructure Program (HSIP) for 133 urban areas in the United States.

Additional work documenting these findings has been undertaken under Task AK-2-3475, Communications and Networking Technologies, for the Deputy Assistant Secretary of Defense, Research.

Appendix A. Digital Elevation Model Tutorial

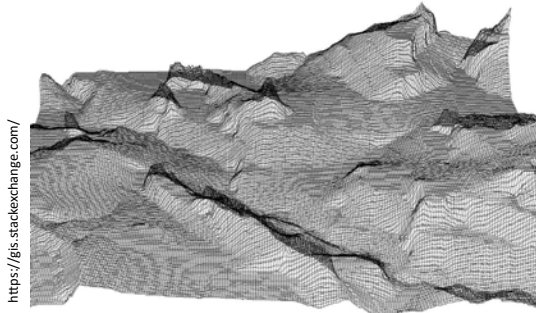
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Increased availability of digital elevation data in well-known formats, often providing global or near-globe coverage, has created opportunities for new users from other technical domains to discover and download digital elevation data for almost any area of interest. It is not uncommon, however, to know little more about the data, generically described as Digital Elevation Models (DEM), than the spacing of the horizontal grid and the file format.

This presentation attempts to present the new user with some context regarding DEM sources and characteristics with particular emphasis on data sets covering the coterminous United States.

Digital Elevation Models (DEM)



DEM displayed in perspective as a wire-frame model

- Display
- Overview
- DEM Level 2 (30m) comparison
- USGS National Elevation Data
- IFSAR-derived DEM Level 4 (5m)
- DEM Level 5 (1m) with features
- Wrap-up



14

A Digital Elevation Model (DEM) is a gridded representation of a terrain surface where each grid post is an elevation (terrain height) value.

Increased availability of digital elevation data in well-known formats, often providing global or near-globe coverage, has created opportunities for new users from other technical domains to discover and download digital elevation data for almost any area of interest. It is not uncommon, however, to know little more about the data, generically described as Digital Elevation Models (DEM), than the spacing of the horizontal grid and the file format.

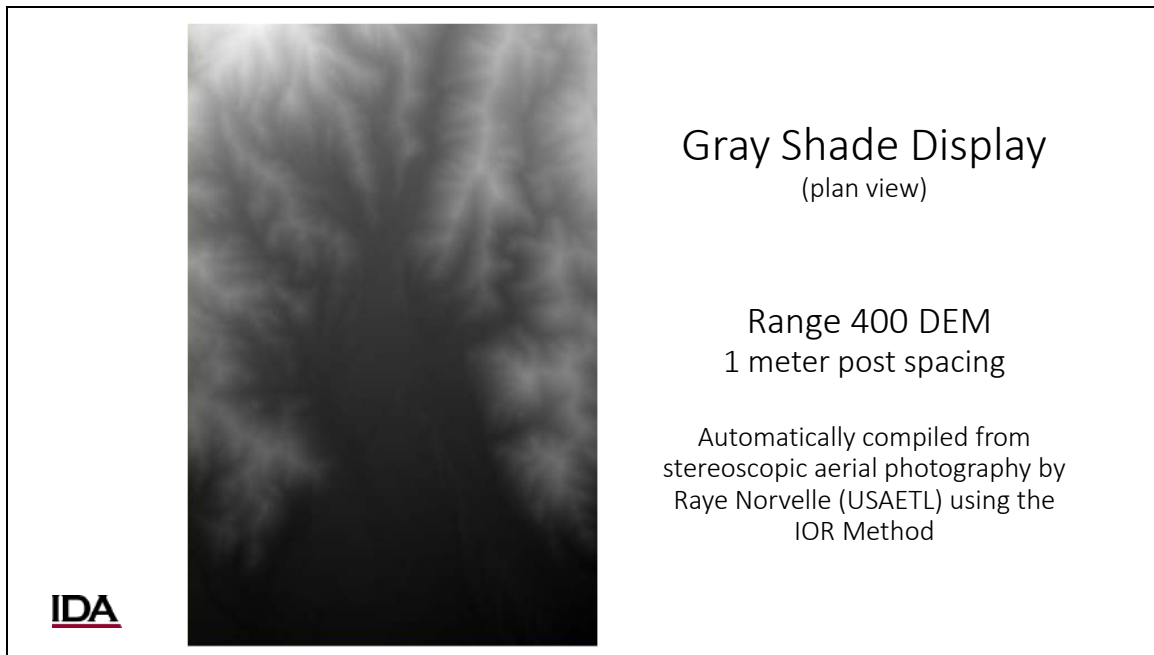
Given that there are many ways to display a DEM, several examples are presented. The above chart presents a perspective view of a wire-frame model that depicts the grid lattice.

An overview discussion introduces DEM nomenclature and taxonomy as well as critical concepts regarding the generation of DEM from disparate sources, technologies, and methods.

DEM Level 2 (30m grid) coverage from four readily available DEM sources are compared over the Table Mountain research site at Longmont, Colorado, to emphasize the differences achieved in representing the terrain surface.

A Level 4 DEM (5m grid) derived using IFSAR technology is also considered.

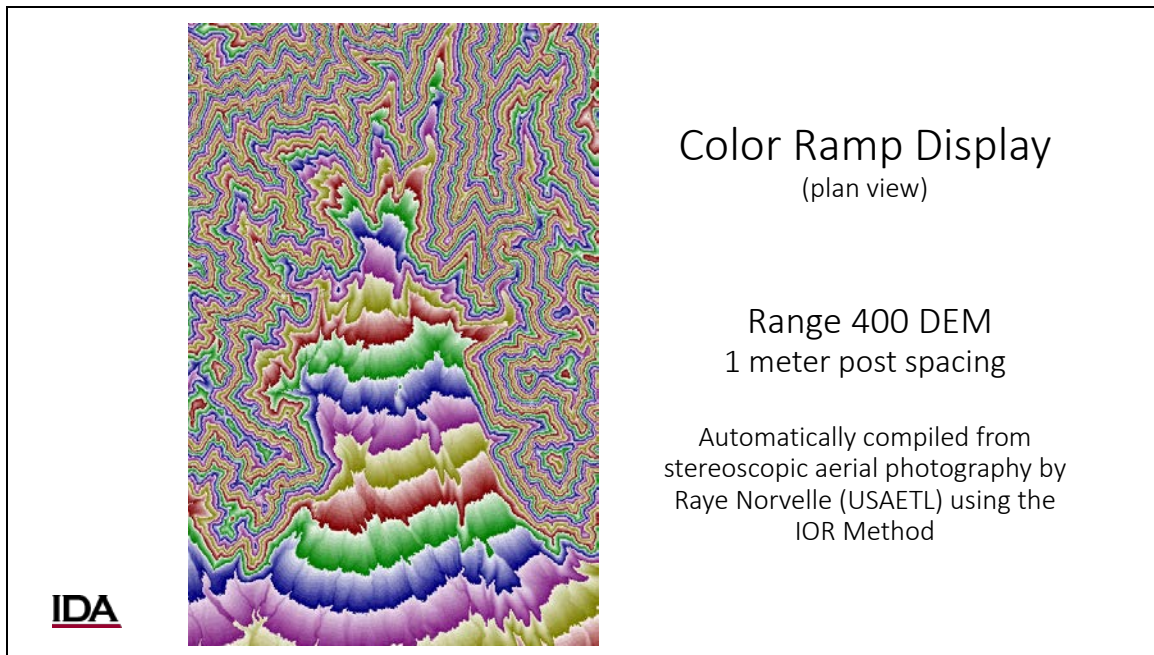
Finally, a new generation of LIDAR-derived Level 5 DEM (1m grid) is presented emphasizing the Homeland Security Infrastructure Program (HSIP) with coverage for 133 US cities that includes extracted building and tree features.



Three charts illustrate plan-view methods used to display DEM. The data set has a grid- or post-spacing of 1 meter covering Range 400, a Marine Corps live-fire training area at Twentynine Palms, California. The DEM was automatically compiled from stereoscopic aerial photography by Raye Norvelle at the US Army Engineer Topographic Laboratory using the Iterative Ortho Refinement (IOR) Method.

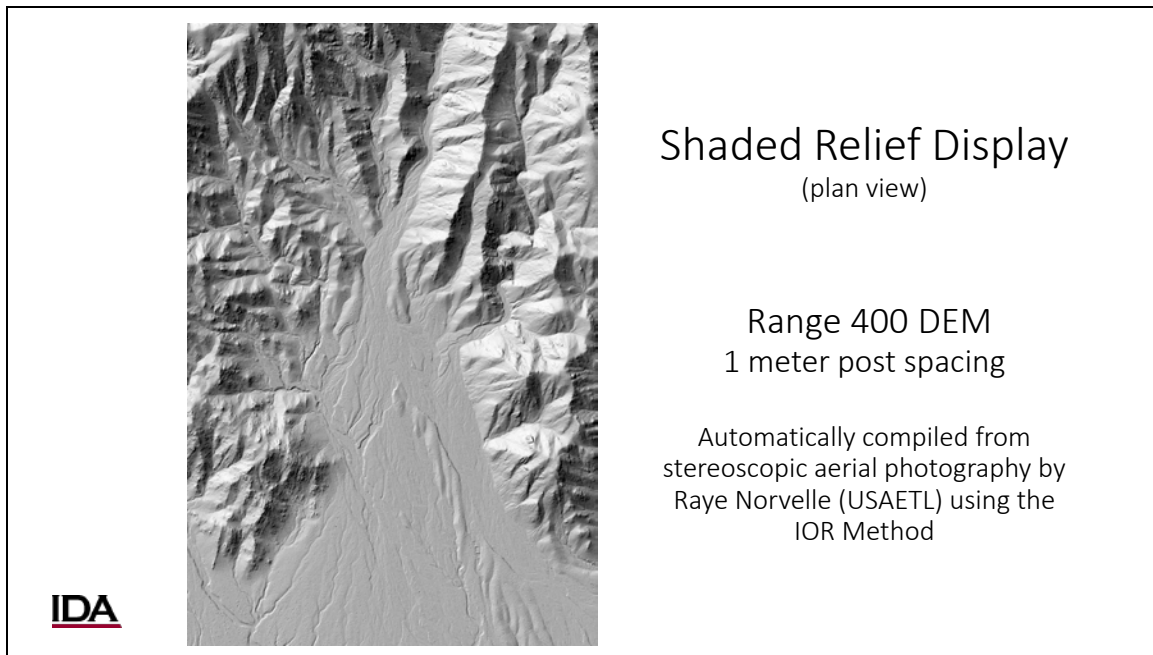
In this “gray-shade” display, each post has been assigned a value ranging from 0 to 255 with the lowest elevation value assigned 0 (black) and the highest elevation value assigned 255 (white).

While frequently used, the Gray Shade Display is not effective in depicted small changes between posts in the DEM.



Color is frequently used for DEM display where a “palette” is used to assign specific colors to the range of elevation values. Continuous color ramps are most commonly used. A typical color palette may use shades of blue for elevations below sea level, shades of green for low elevations above sea level gradually transitioning to shades of yellow, then shades of orange, and finally shades of gray leading to white at the highest elevations; however, there is complete latitude regarding color assignments with many diverse implementation to meet cartographic or aesthetic objectives.

In this example, repetitive color ramp was designed by George Kroenung at the National Geospatial-Intelligence Agency to highlight DEM anomalies for visual detection.



For general use, I prefer the Shaded Relief or Hill-Shade display shown here. Typically, shaded relief images are created assuming solar illumination from the northwest at a angle of 30° to 45°.

Generation of shaded relief images is supported by most Geographic Information Systems (e.g., ArcGIS, GeoMedia, QGIS) and special geospatial elevation applications (e.g., Global Mapper, MicroDEM, GAIT).

Some of the example that follow will use shared relief displays from Global Mapper, an inexpensive, but powerful commercial, and GAIT (Geospatial Analysis Integrity Tool), a specialized application developed by IDA for the National Geospatial-Intelligence Agency (NGA).

Overview

Digital Elevation Model (DEM)
Level of Detail and Nomenclature

Level	Post Spacing		Usage
	arc-sec	meters	
0	30	~ 1,000	Global
1	3	~ 90	Regional
2	1	~ 30	
3	0.4	~ 12	
4	0.11	~ 3	Local
5	n/a	1	

- DEM products are increasingly available
 - Not difficult to find and easy to download
- All DEM products are not created equal
- Characteristics and quality varies with the data source, technology and production method
 - Carto
 - Stereo
 - IFSAR
 - LIDAR



18

In the 1970s, the Defense Mapping Agency (DMA) published Digital Terrain Elevation Data (DTED) as both a military standard format and a product. Three DTED classes were specified: Level 0 with a post spacing of 30 arc-sec (~1 kilometer at the mid-latitudes); Level 1 with 3 arc-sec post spacing (~ 30 meters); and Level 2 with 1 arc-sec post spacing (~ 30m).

Actual production focused on DTED Level 1 from National Technical Means over priority Sino-Soviet regions.

In 1996, DMA cooperated with other mapping agencies to publish DTED Level 0 with global coverage. Similar 30 arc-sec products followed including GTOPO30 (1997), GLOBE (1998), SRTM30 (2003), and GMTED (2010).

In recent years, higher resolution DEM have become available and the taxonomy has been extended to describe Levels 3, 4, and 5. Unlike the formal DTED specification (Levels 0, 1, and 2), these higher resolution categories are largely ad hoc with some variability. Subsequent charts here focus on Level 2 (~ 30m) and Level 5 (1m) DEM based on contemporary availability and relevance.

As DEM products become increasingly available and accessible via Internet search and download, it is important to understand that not all DEM products are created equal. DEM characteristics and quality will vary depending on the data source, technology, and production method. The following charts introduce the four principle DEM generation technologies: cartographic, stereoscopic, IFSAR, and LIDAR.

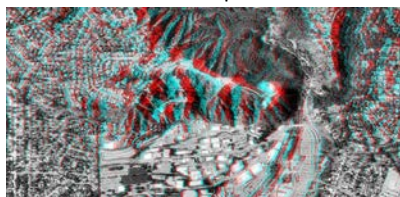
DEM Generation Technologies

Cartographic (vector-to-raster)



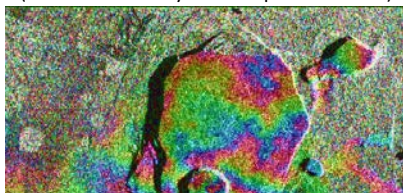
Credit: USGS

Stereo Compilation



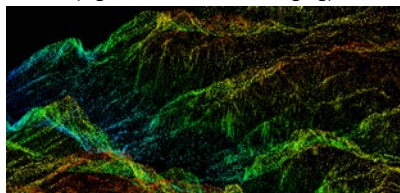
Credit: NASA/JPL-Caltech

IFSAR
(Interferometric Synthetic Aperture Radar)



Credit: NASA/JPL-Caltech

LIDAR
(Light Detection and Ranging)



Credit: Orefind

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Although use of aerial photography for mapping and reconnaissance came into its own in World War II, opto-mechanical stereo plotters have been used to plot contour lines for topographic maps since the 1930's.

Initial efforts to generate DEM in the 1960's relied on digitizing analog contour lines and vector-to-raster conversion. Similar, although more sophisticated, cartographic techniques continue to be employed routinely.

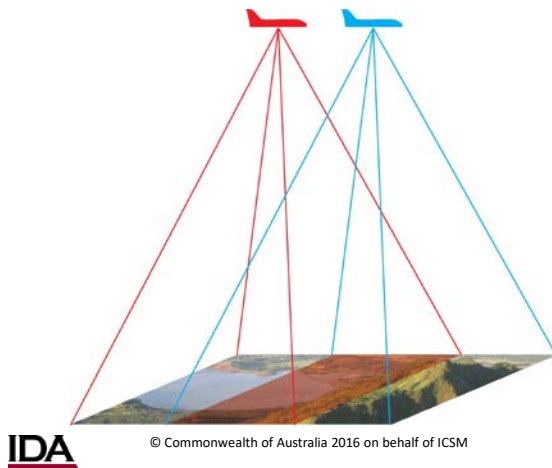
Concurrently, the first stereo correlator was developed for the Army Map Service to automatically generate DEM directly from analog stereo photography. Similar, although more sophisticated, stereoscopic techniques are being used today to extract DEMs from digital stereo imagery acquired from airborne and spaceborne platforms.

In the 1990's, interferometric techniques were applied to extract elevation data from multiple Synthetic Aperture Radar (SAR) images. These techniques are known as IFSAR. Requiring two antennas on airborne and spaceborne platform(s), single-pass IFSAR continues to be a powerful technology to generate global, near-global, and regional DEM.

Lasers have been used to accurately measure distance since initial experiments in the 1960's. Early airborne laser sounders and profilers evolved into aerial laser scanners capable of acquiring dense elevation "point clouds" that are routinely processed to generate extraordinary 1 meter DEM. These scanning systems are termed LIDAR.

Traditional Aerial Survey

Standard 60% stereo overlap



Typical aerial survey platform



Wild RC10 camera
(film)



UltraCamX
(digital)

Traditional aerial survey is conducted from aircraft, typical light aircraft, modified to carry one or more downward-looking camera(s). Photo mission typically operate at altitudes ranging from 2 to 10 kilometers above ground level.

Carefully calibrated mapping cameras are designed to have low geometric lens distortion. Traditional film-based camera produce 9" x 9" photographs. In recent years, film-based cameras have been replaced by digital cameras such as Vexcel's UltraCamX seen here.

In either case, a photo mission is designed to capture sequential near-vertical images with sufficient overlap (traditionally 60%) to provide full stereo coverage along the flight line. Large area surveys require multiple adjacent flight lines with sufficient side-lap between them to ensure complete coverage.

Analog Stereo Extraction and Conversion



Wild A10 analog stereo-plotter



Extracted contour lines of constant elevation

- Early DEM were created circa 1960 by digitizing contour lines from 1:250,000 maps for processing with vector-to-raster conversion algorithms
- Army Map Service for the Electromagnetic Compatibility Analysis Center (ECAC)



Precision analog stereo-plotters such as the Wild A10 seen here were used to view and measure stereo pairs of the 9" x 9" frame photos. Viewing a 3D stereo model, the operator would trace out contour lines of constant elevation to the production of topographic maps.

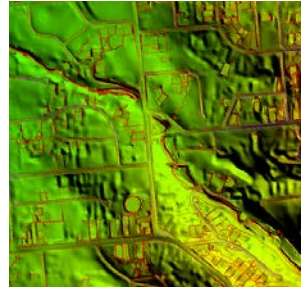
Early DEM were created circa 1960 by the Army Map Service for the Electromagnetic Compatibility Analysis Center (ECAC). Contour lines from 1:250,000 maps were digitized and vector-to-raster conversion algorithms were used to generate DEM. With some effort, these early products can be found in the archives of the US Geological Survey (USGS).

Today's vector-to-raster conversion algorithms are far more sophisticated than early methods. Moreover, much larger scale and higher quality contour lines are being processed. Subsequent charts will illustrate USGS National Elevation Data (NED) that is derived from contemporary 1:24,000 contour lines.

Digital Stereo Extraction



Softcopy Stereo Workstation



Extracted Feature and Elevation Data

- Interactive 3D extraction of features (e.g., roads, lakes, buildings, towers)
- Automated extraction of gridded elevation data (DEM) by stereo correlation



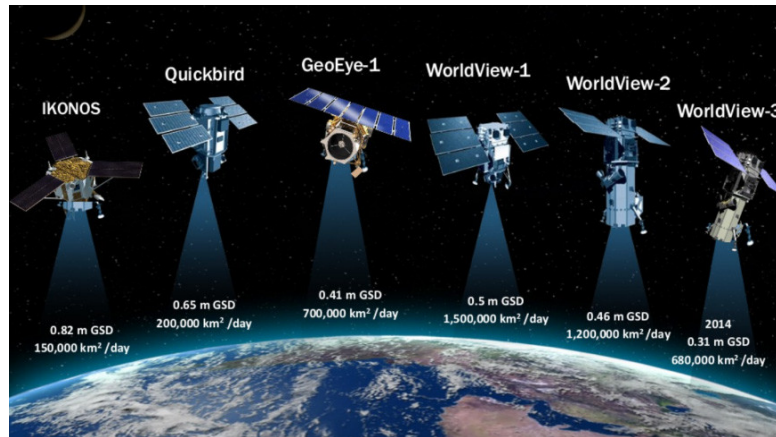
Today, digital stereo workstations have largely replaced analog stereoplotters. Imagery from digital cameras is processed directly and large-format precision scanners are used to digitize mapping photography.

An operator viewing the stereo model will interactively extract 3D features such as roads, lakes, buildings, and towers.

Automated stereo correlation algorithms to automatically extract DEM directly from stereo imagery. We have seen dramatic progress in developing more powerful and robust stereo correlation processes and capitalized on increased computation power as it became available.

The quality of the extracted DEM, however, is always a function of the stereo imagery and the ratio of source pixels to extracted posts. The 1m posts seen in the Range 400 DEM example earlier was compiled from carefully controlled aerial photography digitized to 10 cm pixels. Conceptually, corresponding 10 x 10 pixel patches were matched to extract a single post (100 pixels per post). Later, we will see examples of extracted DEM with as few as 4 pixels per post. The difference in quality of the extracted terrain surface is profound.

Satellite Photography



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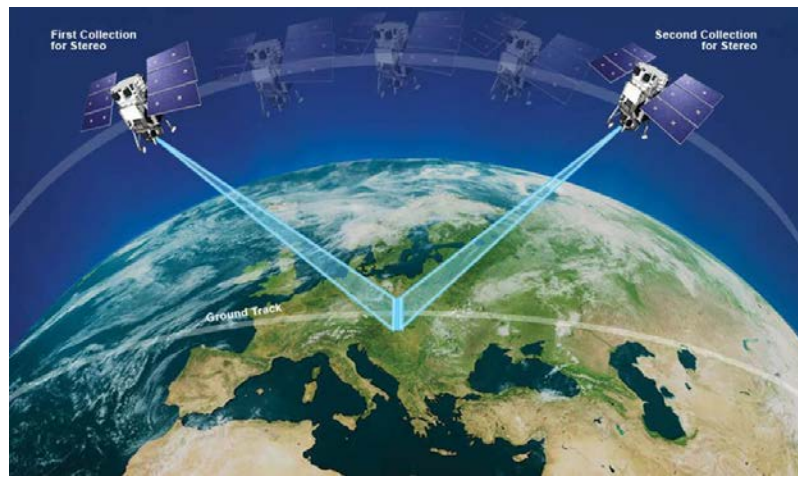
Credit: Digital Globe

Cameras have been mapping from space since 1959 under the now declassified Corona reconnaissance program. The US Government issued the first license to operate a commercial high resolution imaging satellite in 1993.

This chart depicts the suite of imaging satellites operated by the US company Digital Globe. Their latest satellite is WorldView-3 launched in 2014 with capabilities to acquire panchromatic imagery with 0.31 meter (12") resolution and multispectral imagery with 1.24 meter (4'1") resolution.

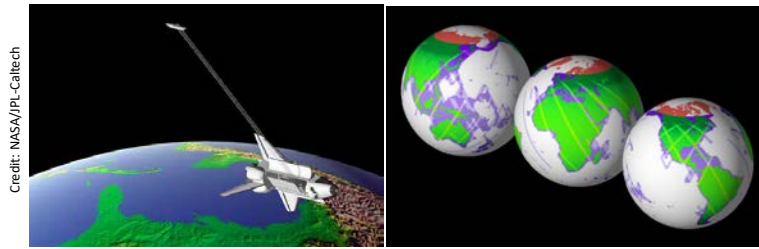
Airbus operates an equally impressive constellation of imaging satellites and there are a number of other commercial ventures.

Satellite Stereo Collection

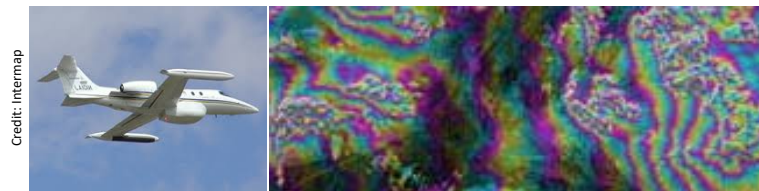


Mapping from space platforms operates under the same principles as mapping from aerial platforms. Collection of stereo coverage – the same landmass imaged from two viewpoints – provides digital data for automated stereo correlation algorithms to generate DEMs.

Interferometric SAR (IFSAR)



Shuttle Radar Topographic Mission (SRTM) in 2000 produced a near-global DEM (56° S to 60° N)



Airborne IFSAR-derived DEM for United Kingdom, Western Europe, and United States

IDA

Synthetic aperture radar (SAR) systems acquire complex signal returns characterized by amplitude and phase. In a conventional configuration, a single antenna transmits and receives the signal and the complex data is processed to provide intensity imagery.

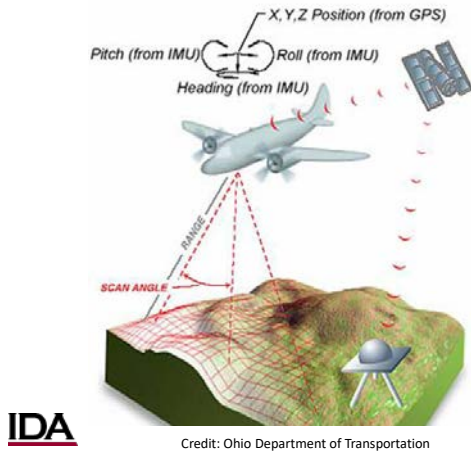
Interferometric processing is possible when there is a second receiving antenna and the baseline between the two antenna is known precisely. Changes in distance to the terrain result in phase shift between the two received signals. Measuring the phase provides the means to generate a DEM. Such an interferometric SAR configuration is known as single-pass IFSAR.

For Shuttle Radar Topographic Mission (SRTM) in 2000, the shuttle Endeavour carried a SAR transmit/receiver antenna in the shuttle bay as well as an extensible 60 meter boom used to deploy a second antenna in orbit. In the course of an 11-day mission, IFSAR data was collected over most of globe from 56° South to 60° North. The data was subsequent processed and finished to generate near-global DEM products published as DTED Level 1 (3 arc-sec or ~ 90 meter post spacing) and DTED Level 2 (1 arc-sec or ~ 30 meter post spacing). For most of the Earth landmass, this was highest resolution DEM ever produced up to that time.

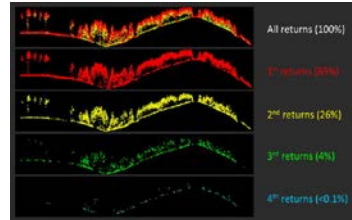
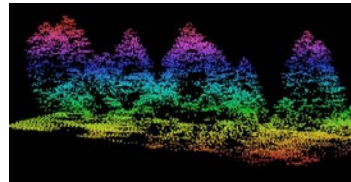
In the early 1990's, radar engineers cleverly packaged two antenna in a pod attached to the belly of a Learjet to provide an airborne IFSAR capability. The system has been owned and operated by Intermap and has generated commercial DEM over the United Kingdom, Western Europe, and coterminous United States.

LIDAR

Airborne LIDAR system: laser scanner, Global Positioning System (GPS), and Inertial Measurement Unit (IMU)



LIDAR Point Cloud



Cross-section view of the 1st, 2nd, 3rd, and 4th returns in a LIDAR Point Cloud

Airborne LIDAR (Light Detection and Ranging) has become a valuable method for generation of high-resolution DEM. From an aerial platform, a laser scanner generates point clouds at up to 400,000 pulses/second. In an operational LIDAR system, differential GPS (Global Positioning System) is used to determine the position of the scanner complemented by an IMU (Inertial Measurement System) to determine the orientation of the scanner. Subsequent processing converts the point clouds to gridded DEM.

Modern LIDAR scanners routinely record multiple returns for each pulse. For solid objects (e.g., bare earth, buildings), there is essentially a single return. Over a forest; however, the first return will typically come from the tree canopy, then returns come from tree branches, and the final return comes from the terrain surface.

Power constraints necessitate operating at relatively modest altitudes (typically 1 to 3 kilometers) with limited swath widths (500 to 1,000 meters). Generation of larger areas requires multiple adjacent flight lines with sufficient side-lap to ensure complete coverage. Precise measurement of scanner position and orientation enable construction of “seamless” coverage from multiple acquisitions.



NTIA/ITS Research Site at Table Mountain (Longmont, Colorado)

DEM Level 2

Comparison of four publicly available 30m DEM from disparate sources and production methods



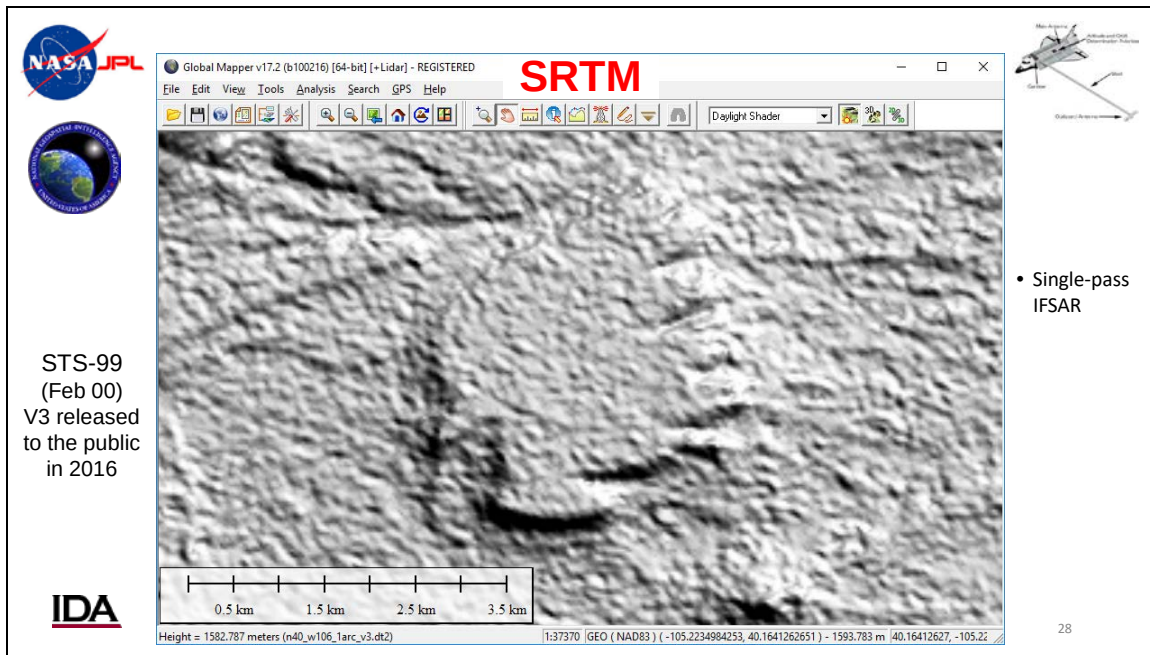
- SRTM
- ASTER
- ALOS
- NED1

27

With the public release of SRTM Level 2 data as well as the ASTER and ALOS global data sets, DEM Level 2 with a post spacing of 1 arc-sec (~ 30 meters) is readily available. For North America, another 1 arc-sec elevation data set termed National Elevation Data (NED1 or 3DEP) is published by the US Geological Survey (USGS) as part of The National Map.

The following charts compare coverage from these four disparate sources over Table Mountain mesa near Longmont, Colorado. Table Mountain is well-documented as a field site and radio quiet zone operated by the Institute for Telecommunication Sciences (ITS), National Telecommunications and Information Administration (NTIA).

The Table Mountain mesa is roughly 3 kilometers by 3 kilometers in area with a relatively smooth terrain surface. At 30 meter post spacing, the Level 2 data corresponds to DEM dimensions of 100 posts x 100 posts. This large scale is well-suited to visualizing the terrain surface represented in these disparate DEM.

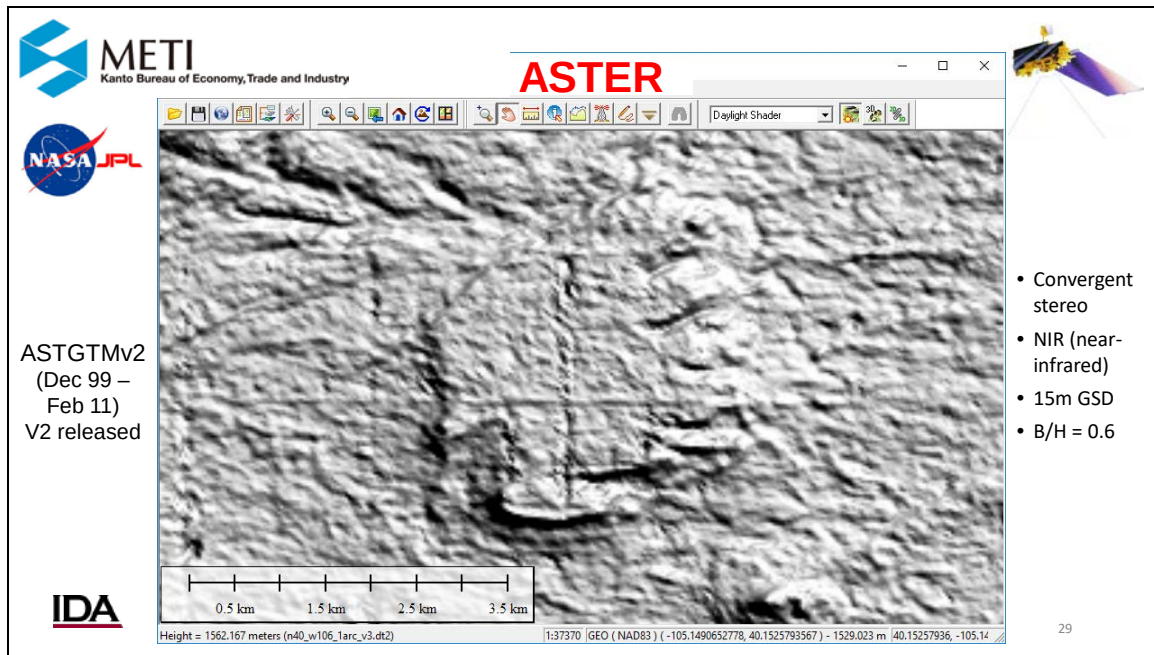


The Shuttle Radar Topographic Mission (SRTM) was a joint effort between NASA and NGA. The resulting elevation data was also distributed by USGS.

SRTM data was acquired in February 2000, processed at the Jet Propulsion Lab over subsequent years, and then edited by NGA contractors to remove noisy surfaces over water bodies. Initially, distribution of Level 2 data was constrained to the DoD. Public release was announced in 2015.

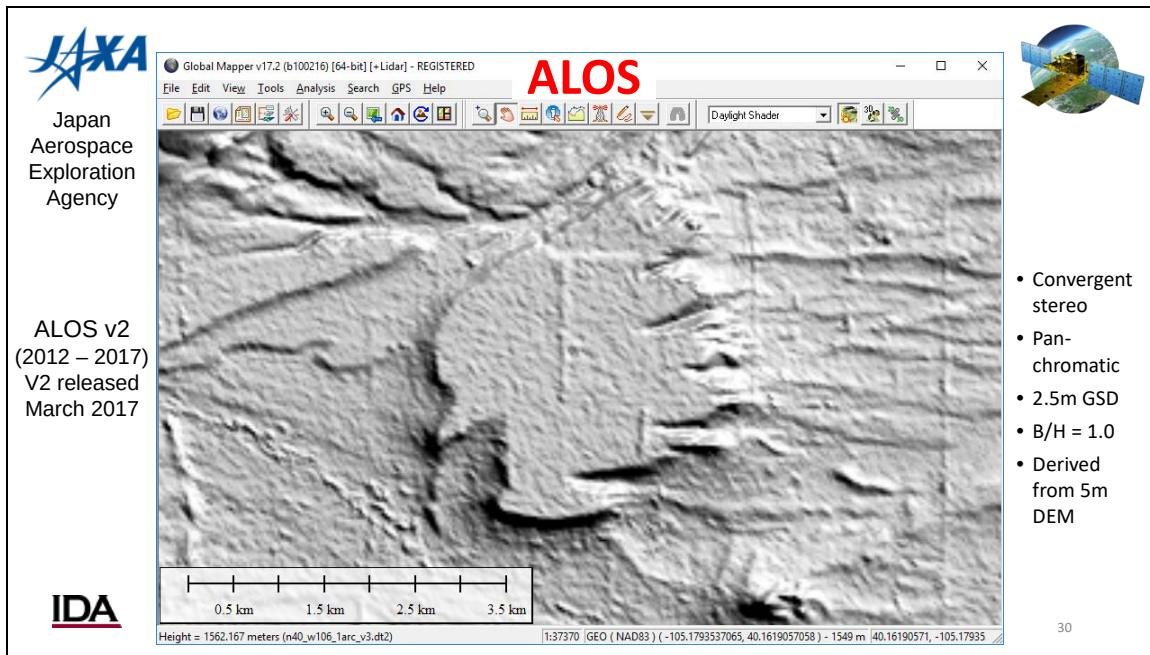
The key characteristic of the SRTM DEM is “lumpiness” in the terrain surface. The lumps range from approximately 3 to 5 meters in height with irregular spacing between lumps on the order of 100 meters. IFSAR subject matter experts have characterized these artifacts as the product of antenna “shot noise” seen in all IFSAR-derived DEM. Numerous efforts have been made to filter these artifacts with little success.

While near-global SRTM coverage proved to be extremely valuable for most of the Earth where no such data previously existed, the anomalies are problematic for applications operating close to the terrain surface such as flood prediction and terrestrial line-of-sight.



The ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) Global Digital Elevation Model (GDEM) was a joint effort between Japan's Ministry of Economy, Trade, and Industry (METI) and NASA. GDEM V1 was publically released in 2009 and an enhanced GDEM V2 followed in July 2011.

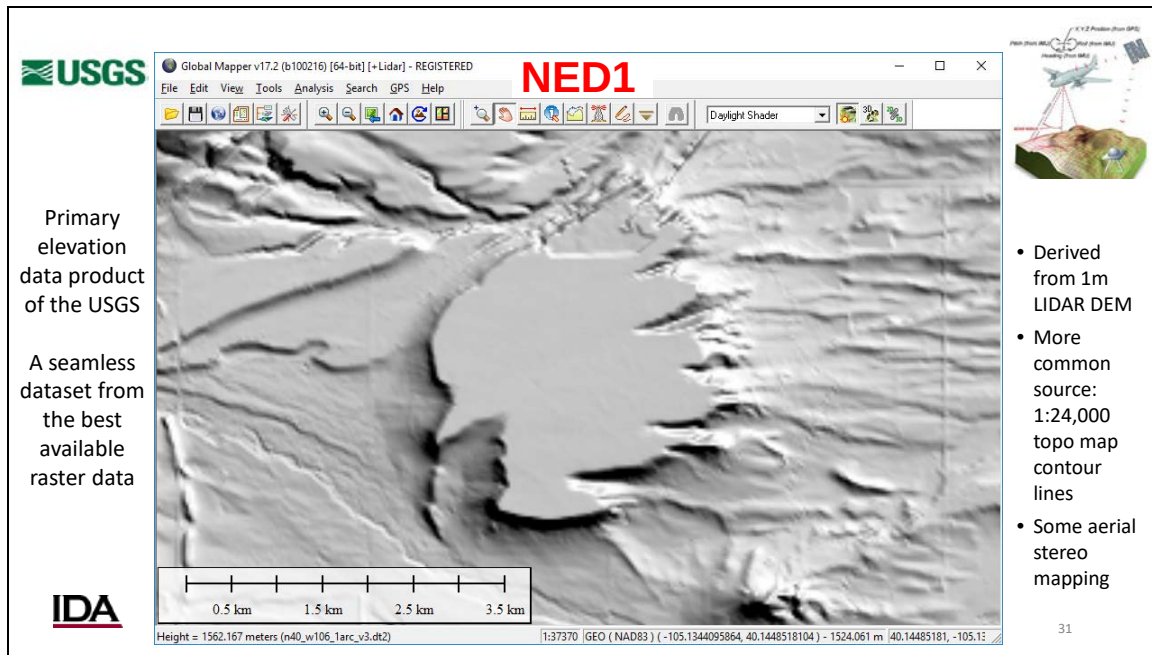
The ASTER GDEM was generated by automated stereo correlation of imagery from convergent near-infrared cameras on the ASTER satellite. At nadir, this imagery has a ground-sample-distance (GSD) or pixel size of 15 meters. While the base-height ratio (B/H) of 0.6 is well-suited to stereo mapping, generation of a 30 meter DEM from this imagery must rely on a sparse 4:1 ratio of pixels-to-posts. The leads to the anomalous ("lumpy") terrain surface seen here over and around Table Mountain.



This global DEM was released to the public by the Japan Aerospace Exploration Agency (JAXA) in 2017. It was generated from a 5 meter DEM generated by automated stereo correlation of imagery from convergent PRISM (Panchromatic Remote-sensing Instrument for Stereo Mapping) cameras carried by Advanced Land Observing Satellite (ALOS).

At nadir, this imagery has a ground-sample-distance (GSD) or pixel size of 2.5 meters. While the base-height ratio (B/H) of 1.0 is well-suited to stereo mapping, generation of a 5 meter DEM from this imagery must rely on a sparse 4:1 ratio of pixels-to-posts.

Down-sampling the original 0.15 arc-sec (~ 5 meter) DEM to 1.0 arc-sec (~ 30 meter) DEM was performed by a “mean/median filter of a 7x7 kernel” resulting in the terrain representation of Table Mountain seen here.



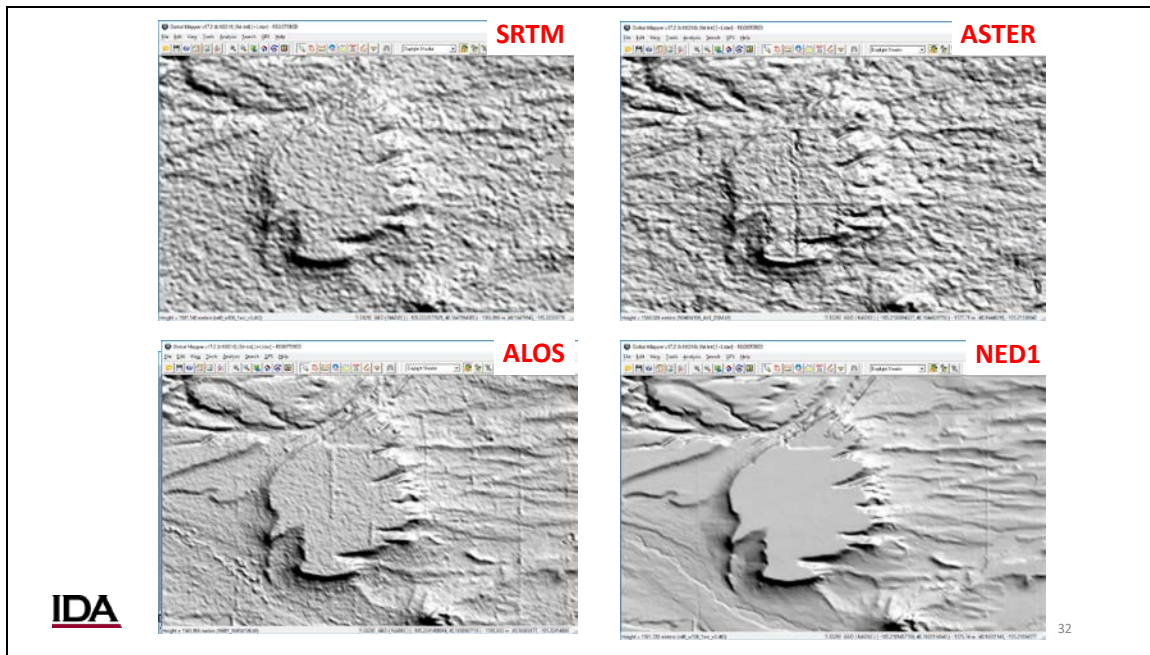
NED, also known as 3DEP, is the primary elevation product of the USGS. USGS describes NED as a “seamless dataset of the best available raster data”.

In practice, the majority of the 1 arc-sec DEM is derived from 1:24,000 topographic map contour lines using sophisticated vector-to-raster algorithms, often applying additional hydrologic constraints. The resulting DEM benefits from the quality of the source data and considerable attention to detail.

In some cases, DEM has been derived directly from stereoscopic aerial photography. Some coverage has been acquired with modern digital mapping cameras and processed with automated stereo correlation algorithms. Specific details on GSD and pixel-to-post ratio are not known, but I assume that is far greater than 4:1 seen previously and in the neighborhood of 100:1 used for the Range 400 example.

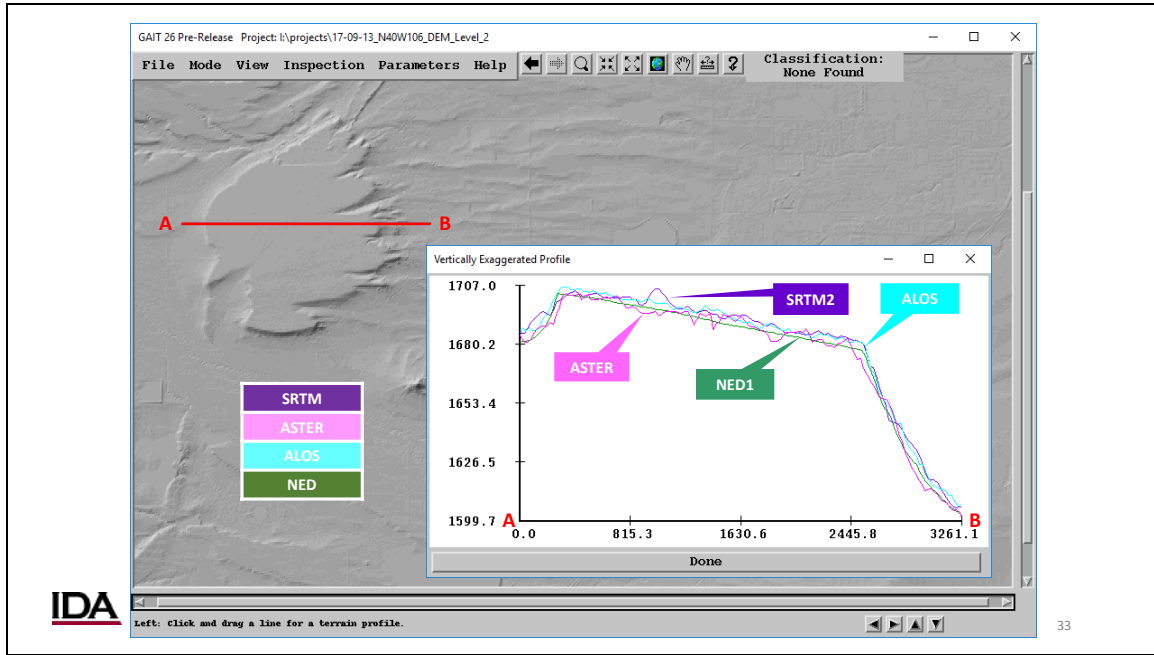
Current USGS acquisition emphasizes use of LIDAR where point clouds are processed to generate 1 meter DEM. Where available, 1 meter DEM are resampled to produce 1/9 arc-sec (~ 3 meter), 1/3 arc-sec (~ 10 meter), and 1 arc-sec (~ 30 meter) NED.

LIDAR source data was used to generate the NED coverage over Table Mountain.



All four of these Level 2 DEMs have identical horizontal post spacing of 1 arc-sec or ~ 30 meters. Each data set is the product of one or more national space or mapping agencies. The data sets are known to digital mapping practitioners and readily discoverable by non-specialists. Some popular applications link to directly to one or more of these products. All can be downloaded directly without charge.

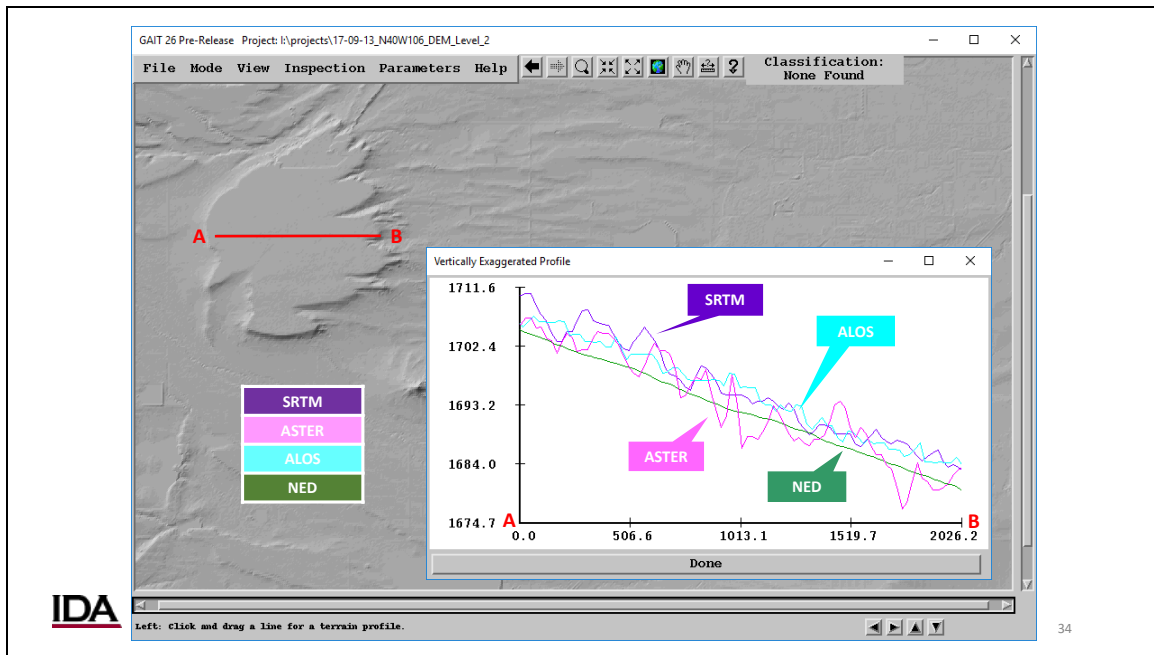
As described, there different technologies – IFSAR, stereo, and LIDAR – have been employ. Visual comparisons suggest some of different characteristic in the resulting terrain surfaces. In the following charts, comparative terrain profiles highlight the differences.



A GAIT project has been constructed with registered 1 arc-sec SRTM, ASTER, ALOS, and NED digital elevation models.

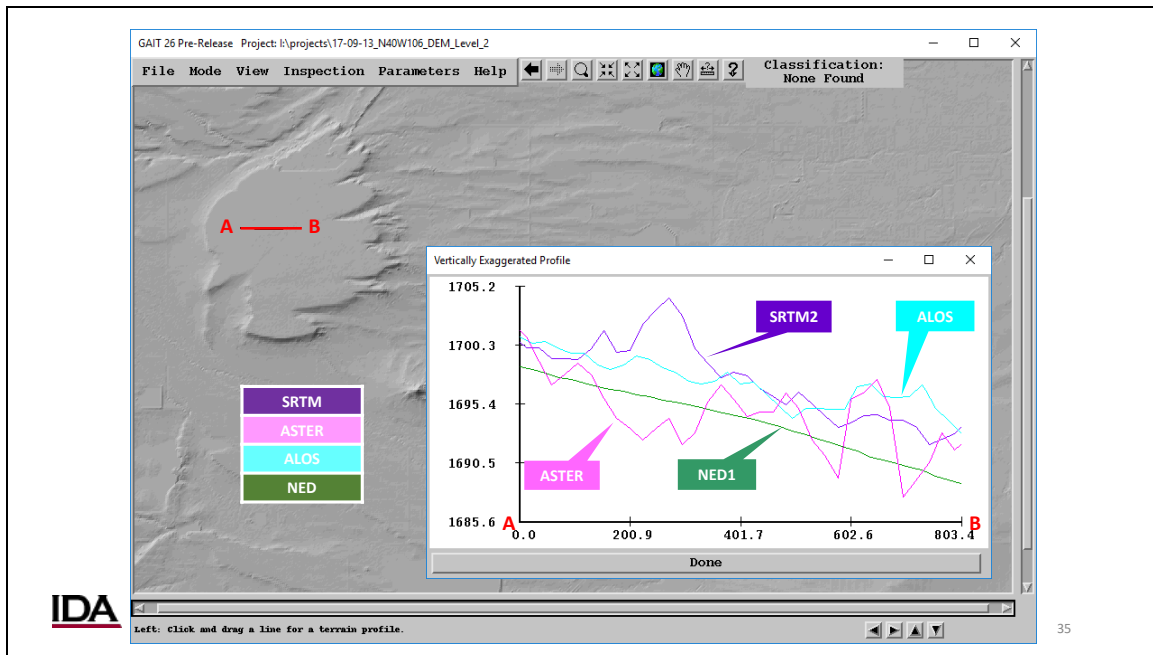
As seen above in the upper left, a profile line has been specified from “A” to “B”. In the resulting graph, the 3261 meter line from “A” to “B” is represented on the X-axis and elevation values (1599 to 1707 meters) are plotted on the Y-axis.

While “lumpiness” in SRTM and ASTER, and to lesser extent in ALOS is evident, the elevation range on the Y-axis (over 100 meters) results in closely aligned profiles. By specifying a shorter profile that reduces the range of elevation, differences can be studied more effectively.



With the reduced baseline limited to the surface the mesa, the vertical range is expanded to 37 meters. Now it more obvious that NED represents a well-behaved sloping terrain surface consistent with the gently sloping mesa. SRTM, ASTER, and ALOS present varying degrees of unnatural undulation introduced by IFSAR or poorly constrained stereo correlation.

A third and final chart for this data set further reduces the baseline to expand display of the differences.



This 803 meter baseline further expands the vertical range 20 meters. At this increased resolution, the NED profile continues to show a relatively constant slope. The characteristic “lumpiness” of the SRTM suggests vertical noise in the order of 3 to 5 meters with a vertical bias of 2 to 3 meters above NED. Arguably, ASTER shows similar or perhaps slightly greater variability with little bias with respect to NED. ALOS displays vertical excursions on the order of 2 meters with bias on the order of 2 meters above NED.

Depending on the application, these product-specific anomalies may be negligible or highly significant. For many parts of the world, ALOS or ASTER provides 1 arc-sec elevation data where no such data was previously available. For North America, however, the USGS National Elevation Data represents an extraordinary existing resource from a national agency with a continuing commitment to maintaining and enhancing the data set.

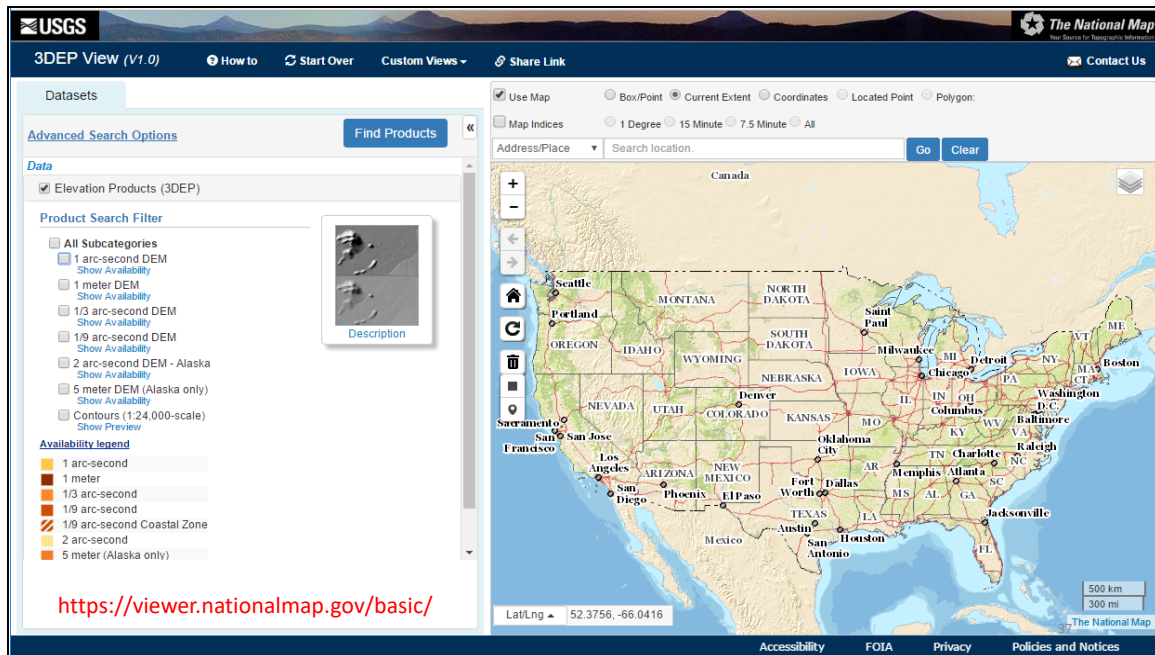
USGS NED 1 and NED 1/3 National Elevation Data

Coverage and Dissemination from
The National Map



36

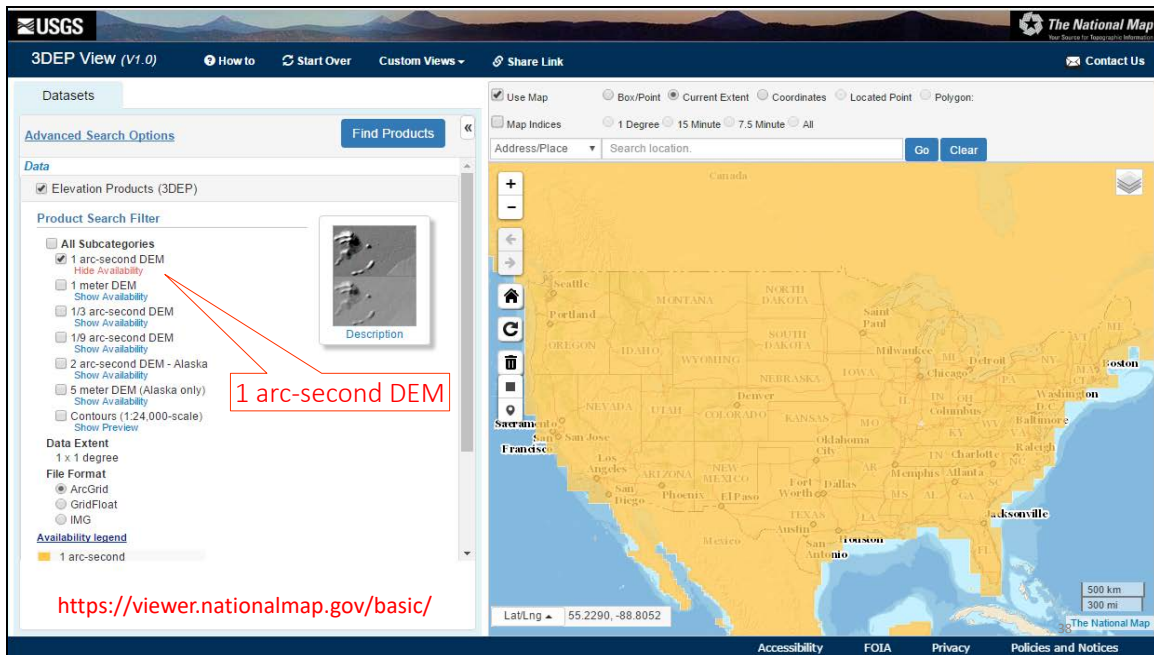
The next charts focus on the “Elevation Products (3DEP)” section of USGS web site for The National Map (TNM) at <https://viewer.nationalmap.gov/basic>).



From “The National Map” window, clicking on the “Elevation Product (3DEP)” button and then clicking on “Availability legend” text below leads to the window shown here.

Products discussed in this presentation include:

- 1 arc second DEM
- 1 meter DEM
- 1/3 arc second DEM



Clicking on the “1 arc-second DEM” button and the associated “Show Availability” text leads to the window shown here.

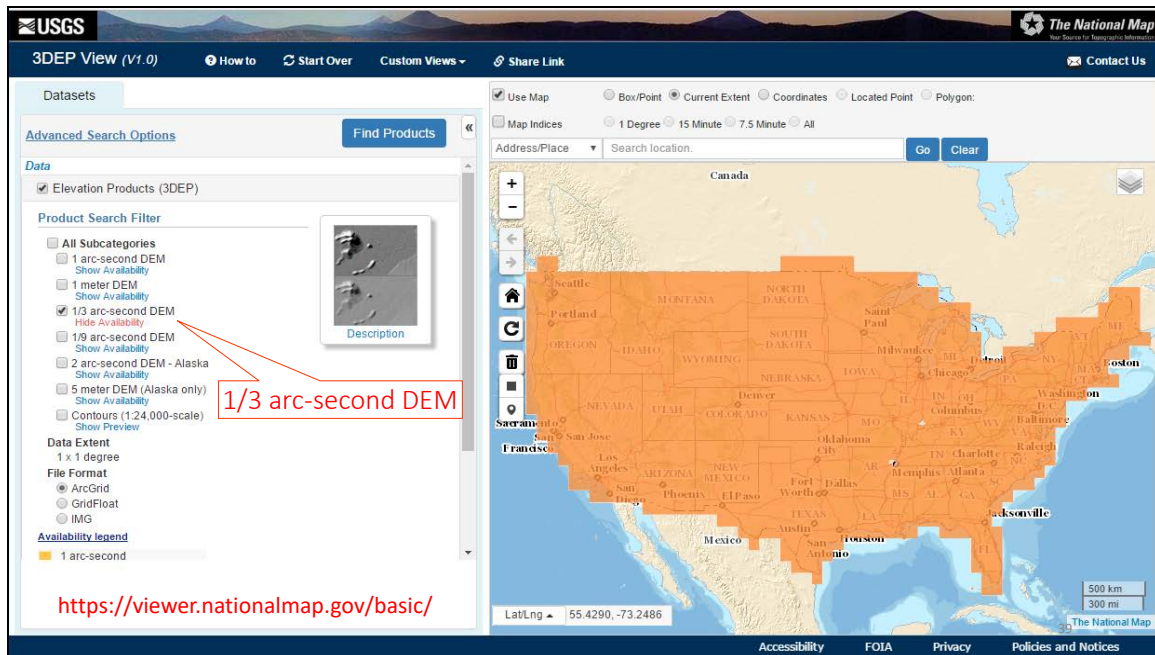
Note that available 1 arc-sec (~ 30 meters) DEM covers most of the coterminous United States, Canada, and Mexico.

Several mechanisms are supported for the user to define a specific area-of-interest. Specific data sets can then be downloaded in 1° x 1° blocks (nominally 100 km x 100 km).

One of three well-known data formats must be selected:

- ArcGrid (an ESRI format)
- GridFloat (an ESRI format)
- IMG (ERDAS Imagine format now supported by Hexagon Geospatial)

Each format supports lossless exchange of the raster elevation data.



Clicking on the “1/3 arc-second DEM” button and the associated “Show Availability” text leads to the window shown here.

Note that available 1/3 arc-sec (~10 meter) DEM covers almost all of the coterminous United States.

Specific data sets can request and then downloaded in the selected format in 1° x 1° blocks.

Code	USGS Production Method (PMETHOD)
0	Unknown
1	Electronic Image Correlation (specifically GPM II)
2	Manual Profiling
3	DLG2DEM
4	DCASS
5	LT4X (vectorization software)
6	Complex polynomial interpolation, such as ANUDEM
7	LIDAR
8	Photogrammetric mass points and break lines
9	Digital camera correlation
10	IFSAR
11	Other remote sensing technique
12	Topobathy

IDA

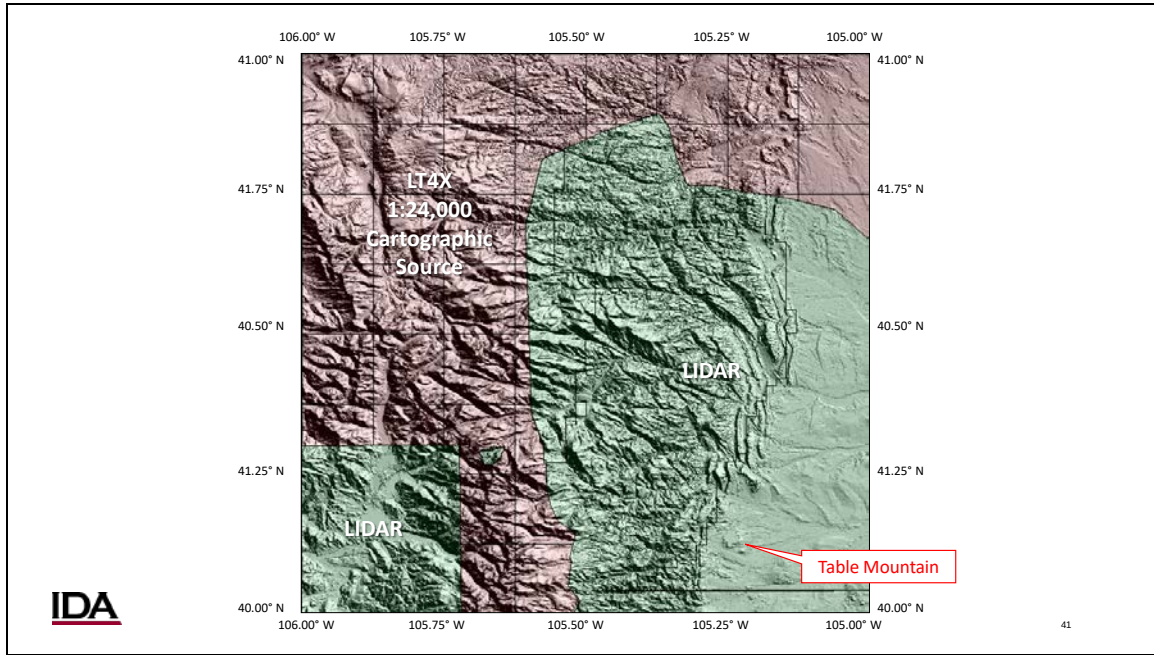
40

Download of each 1 x 1 data block or cell includes a set of ancillary documents as well as the specified DEM. One folder with a name based on the geographic coverage ('nxxwxxx') contains a Shapefile of metadata for that cell.

Fields contained in this Shapefile metadata are documented in the NED Data Dictionary (https://nationalmap.gov/3DEP/documents/Data_dictionary_%2020160115.pdf).

One of these field specifies the Production Method (PMETHOD) in one the enumerated codes listed above. The list includes legacy methods no longer in use (e.g., "Manual profiling", "GPM II") as well as current volume methods (e.g., "LT4X", "LIDAR"), and specialty methods (e.g., "IFSAR" for Alaska, "Topobathy" in selected coastal regions).

An example of this PMETHOD metadata is present in the next chart for the cell N40W106 in Colorado that contains Table Mountain.

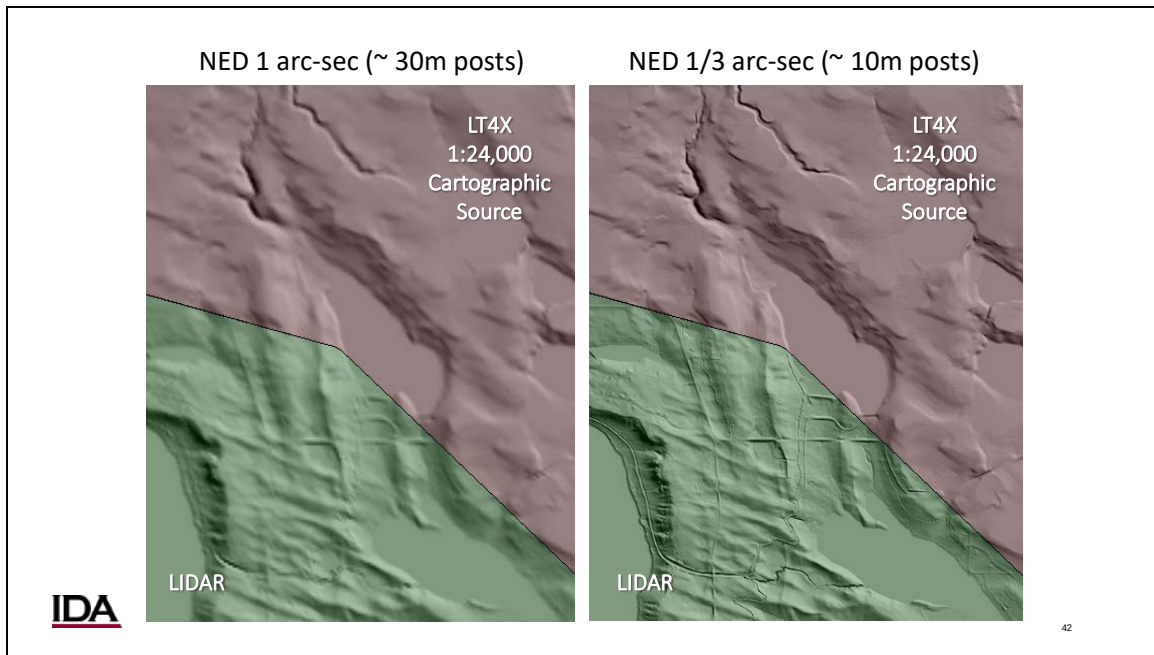


Here is a shaded relief image of NED 1 arc-sec (~ 30m) for the 1° x 1° cell extending from 40° to 41° North and 106° to 105° West in Colorado. The Front Range runs north/south in the east of the cell while Table Mountain lies in the southeast.

Color tints reflect the PMETHOD coding with “LT4X” displayed in red tint and “LIDAR” display in green tint.

LTE4X software is used to generate vector data from scanned line maps. In this case, the metadata listed the specific 1:24,000 topographic map that provided vector contour lines that were converted to raster DEM. LTE4X is the currently the most common production method for NED.

LIDAR indicates DEM or DEM source that was originally generated from LIDAR point clouds. A subsequent chart displays the limited, but growing, coverage of LIDAR DEM in the NED.



These charts highlight an area that is partially generated from LIDAR (green tint) and LT4X (red tint). NED 1 arc-sec (~ 30 meters) is shown on the left and NED 1/3 arc-sec (~ 10 meters) is shown on the right.

Comparing the two DEMs, one can visually discern the higher spatial frequency content of 1/3 arc-sec (~ 10 meter) DEM to the 1 arc-sec (~ 30 meter) DEM. This is not surprising.

Within each DEM, one can visually discern the higher spatial frequency content of LIDAR-derived DEM over the carto-derived DEM. This is not surprising.

In addition, it is also important to note that the cartographic source (1:24:000 contour lines) displays higher spatial frequency content in the 10 meter DEM than the 30 DEM. This is a reflection of the inherent quality of the cartographic source.

At these results (30 and 10 meters), the coterminous United States is well served by these two products. In the future, expanded LIDAR coverage will continue to enhance these products while supporting far more demanding applications such as flood-plain mapping.

DEM Level 4

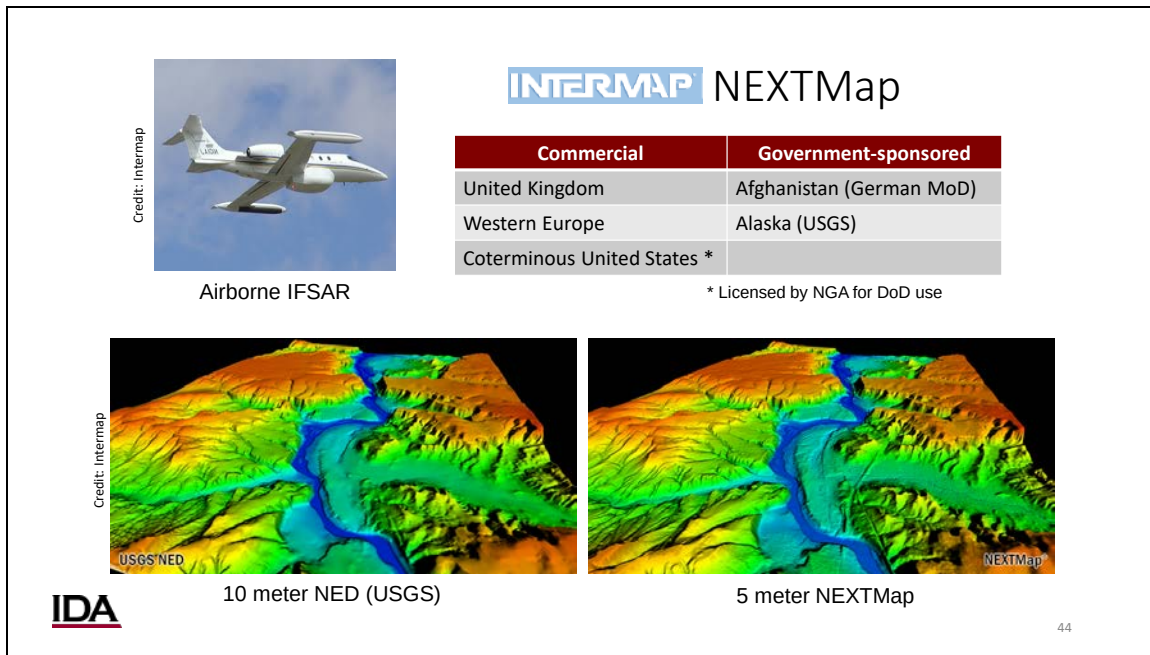
NEXTMap 5m DEM from Airborne IFSAR



43

In addition to the publicly available DEM products previously discussed, there are a few notable commercial DEM products.

The following charts introduce NEXTMap, a commercial 5 meter DEM, derived by airborne IFSAR.



In the early 1990s, DARPA and then the Army Topographic Engineering Center (now the Army Geospatial Center) funded development of an airborne IFSAR system with antennas configured in a pod attached to the belly of a Learjet. Subsequently, the system has been owned and operated by Intermap.

Under Government contract, Intermap generated 5 meter DEM for much of Afghanistan. An on-going campaign is acquiring 5 meter DEM over Alaska for USGS.

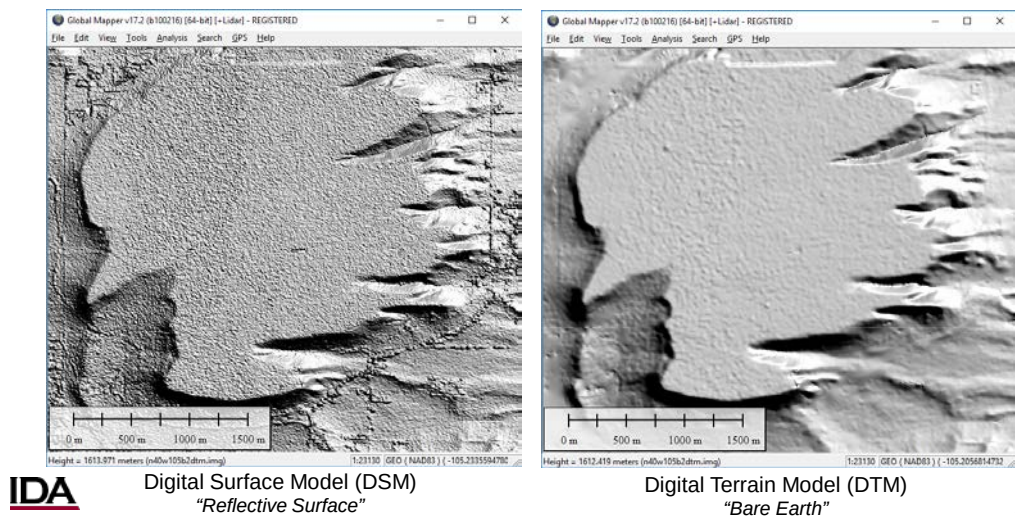
Under corporate funding, Intermap generated 5 meter DEM over the United Kingdom, Western Europe, and coterminous United States for commercial sale with two products: a Digital Surface Model (DSM); and a Digital Terrain Model (DTM).

NGA has licensed the full NEXTMap data of the coterminous United States for use with the Department of Defense.

The original IFSAR is inherently a “reflective surface” DSM. The process that Intermap uses to generate a “bare earth” DTM is not advertised; however, comparisons to 10 meter NED to 5 meter NEXTMap are advertised as seen here.

The following charts compare NEXTMap and NED data over Table Mountain

NEXTMap (5m DEM)



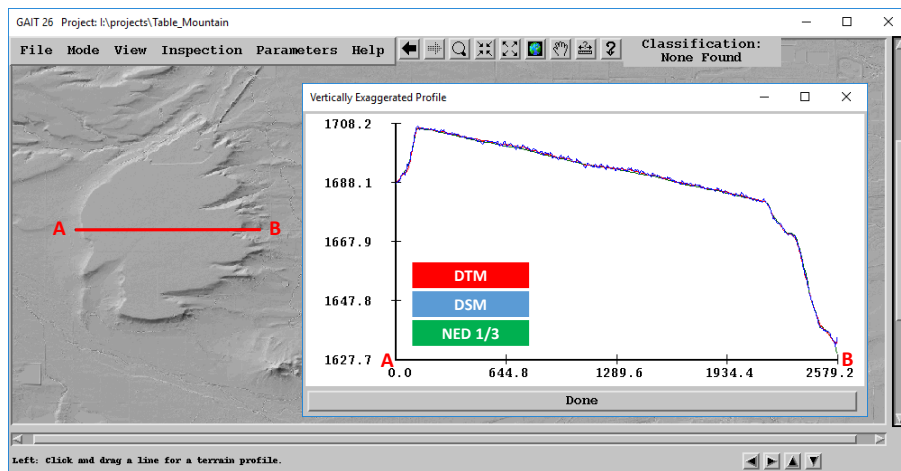
Shaded relief is used to display coverage of NEXTMap 5m DEM over Table Mountain. The data is actually delivered in geographic coordinates with a 0.15 arc-sec post spacing.

The "reflective surface" Digital Surface Model (DSM) is displayed on the left. Note the fine grained texture ("lumpiness") evident across the Table Mountain Mesa.

The "bare earth" Digital Terrain Model (DTM) is displayed on the right. Note reduction in fine grained texture ("lumpiness") seen on the Table Mountain Mesa.

Terrain profiles provide a tool to explore these terrain surfaces further.

NEXTMap (5m DEM)



IDA

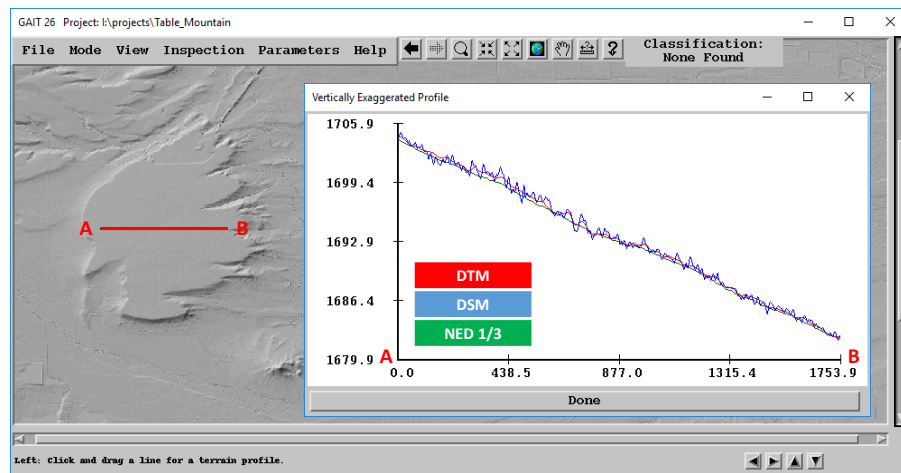
46

A GAIT project has been constructed with co-registered NEXTMap (0.15 arc-sec) and NED 1/3 (0.33 arc-sec) DEM.

As seen to the upper left, a profile line has been specified from “A” to “B”. In the resulting graph, the 2,579 meter line from “A” to “B” is represented on the X-axis and elevation values (1,027 to 1,708 meters) are plotted on the Y-axis.

This resolution results in closely aligned profiles. By specifying a shorter profile that reduces the range of elevation, differences can be studied more effectively.

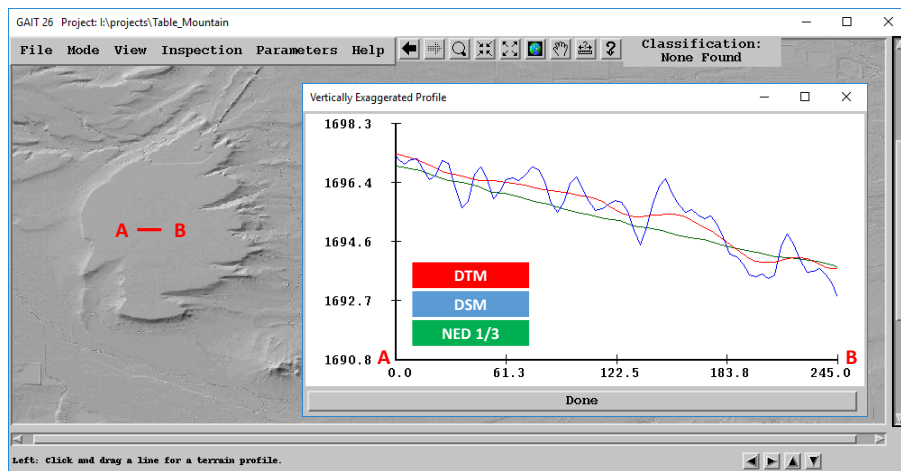
NEXTMap (5m DEM)



With a shorter 1,754 baseline across the mesa, the elevation range is reduced to 1,679 to 1705 meters (26 meters).

The inherent noise in the DSM is readily evident. By reducing the baseline further, differences can be studied more effectively.

NextMap (5m DEM)



Here, a 245 meter baseline centered in the mesa results in a vertical range from 1,691 to 1,698 meters (7 meters).

One again, the NED 1/3 (green) presents a well-behaved constant sloped terrain surface.

The NEXTMap Digital Surface Model (DSM shown in blue) is characterized by an anomalous surface with ~ 2 meter “lumps”.

The NEXTMap Digital Terrain Model (DTM shown in red) is far better behaved with ~ 1m anomalies. This is consistent with some partially effective smoothing process. In the absence of trees or building on the Table Mountain site, assessment of the “bare earth” process on more challenging conditions.

In the absence alternative products (e.g., post-9/11 Afghanistan), NEXTMap products warrant consideration. That is not case for the coterminous United States

DEM Level 5

USGS 1m DEM from LIDAR

LIDAR 1m DEM and Features Extracted LIDAR under the
Homeland Security Infrastructure Program (HSIP)



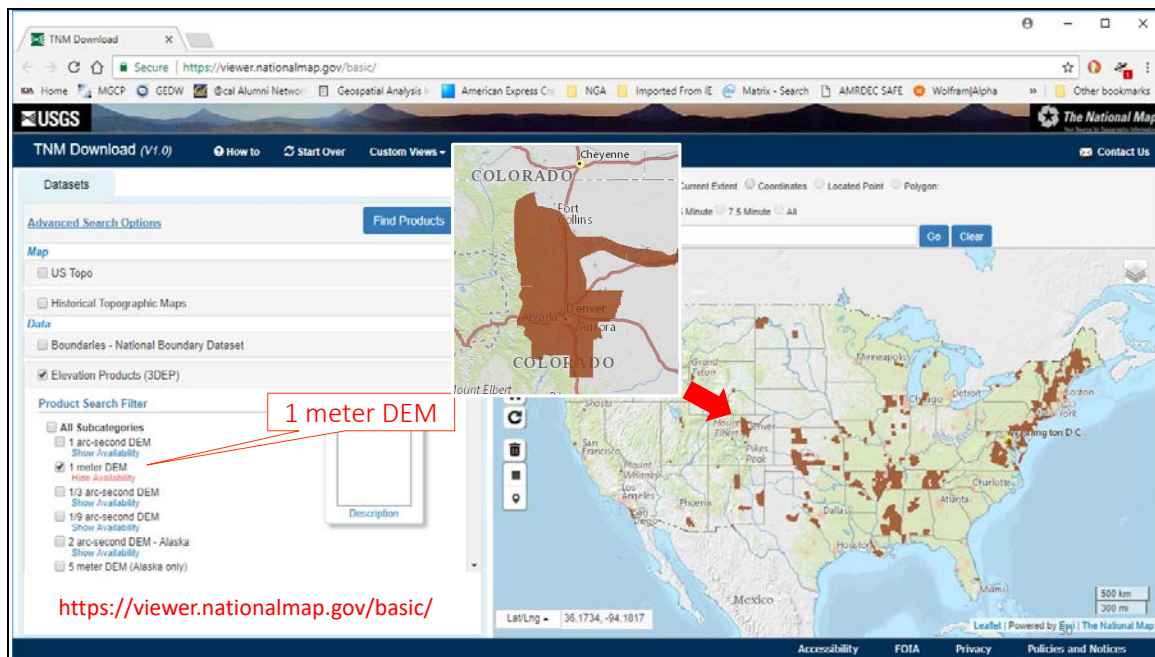
49

The 1 meter DEM of Range 400 seen earlier in this presentation was compiled in the early 1990s from stereoscopic aerial photography. It would be first known 1m DEM produced experimentally with great attention to detail.

Since then, LIDAR technology has revolutionize the mapping profession. While LIDAR scanners acquire data over narrow swaths perhaps 500 to 1000 meters wide and wide area coverage is expensive, LIDAR data is routinely acquired over high-value sites including coastlines, floodplains, rights-of-way, and urban areas.

This following charts high two important sources for the coterminous United States: USGS 1 meter DEM; and 1 meter DEM and features from the Homeland Security Infrastructure Program (HSIP).

Other public sources in Corps of Engineers Districts and the Buckeye Program operated by the Army Geospatial Engineering Center.



For USGS LIDAR coverage, return to the “The National Map” (<https://viewer.nationalmap.gov/basic>), click on the “Elevation Product (3DEP)” button, the “1 meter DEM” button, and then the associated “Show Availability” text.

Available coverage is limited, but will grow under The National Map program.

The enlarged insert depicts the LIDAR coverage of Denver and the Front Range that includes Table Mountain.

HSIP LIDAR-Extracted Data

- Under the Congressionally-mandated Homeland Security Infrastructure Program (HSIP), NGA managed acquisition of LIDAR-extracted data for 133 urban areas within the United States for distribution by GRiD (next chart)
- Data processing and automated feature extraction is performed by specialists under NGA geospatial production contracts
 - A large operational program with state-of-the-art performers
- Each HSIP LIDAR data set includes:
 - “Reflective surface” Digital Elevation Model (1m grid)
 - “Bare earth” Digital Elevation Model (1m grid)
 - Area Building features (Shapefiles with attributes)
 - Point Tree features (Shapefiles with attributes)
 - Area Forest features (Shapefiles with attributes)

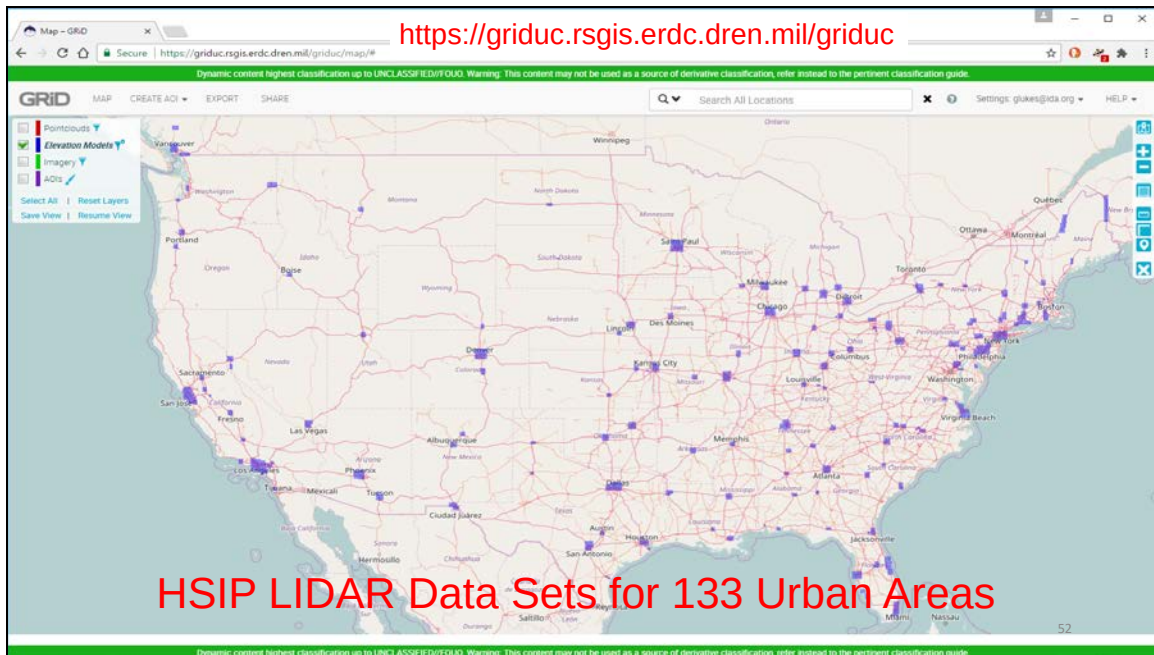


51

Under the Congressionally-mandated Homeland Security Infrastructure Program (HSIP) managed by NGA, airborne LIDAR data has been collected for 133 urban area and processed to provide:

- “Reflective surface” Digital Elevation Model (1m grid);
- “Bare earth” Digital Elevation Model (1m grid);
- Extracted vector data for area Building features (attributed Shapefiles);
- Extracted vector data for point Tree features (attributed Shapefiles); and
- Extracted vector data for area Forest features (attributed Shapefiles).

Today, HSIP point cloud data and DEM are cleared for public release. Extracted feature data is restricted “For Official Use Only (FOUO)”.

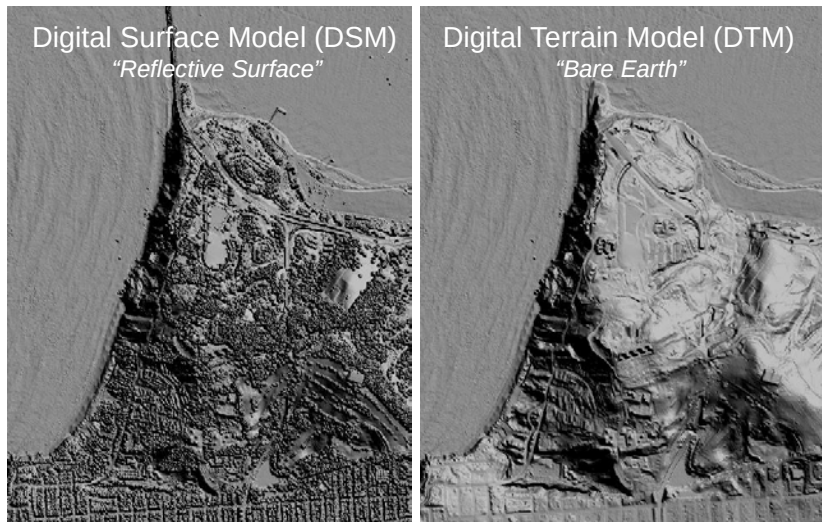


HSIP and other LIDAR data is being distributed from the GRiD web site (<https://griduc.rsgis.erd.c.dren.mil/griduc/>) operated by the Cold Regions Research and Engineering Laboratory for NGA. User accounts are required.

This GRiD coverage map shows the location of the 133 urban areas covered by HSIP LIDAR acquisition and processing.

From the GRiD Map menu under “Data Layers”, HSIP point cloud and DEM are listed under “US Cities – Public” while vector feature data is listed under “US Cities – USMI”.

LIDAR-derived DEM (1m posts)



IDA

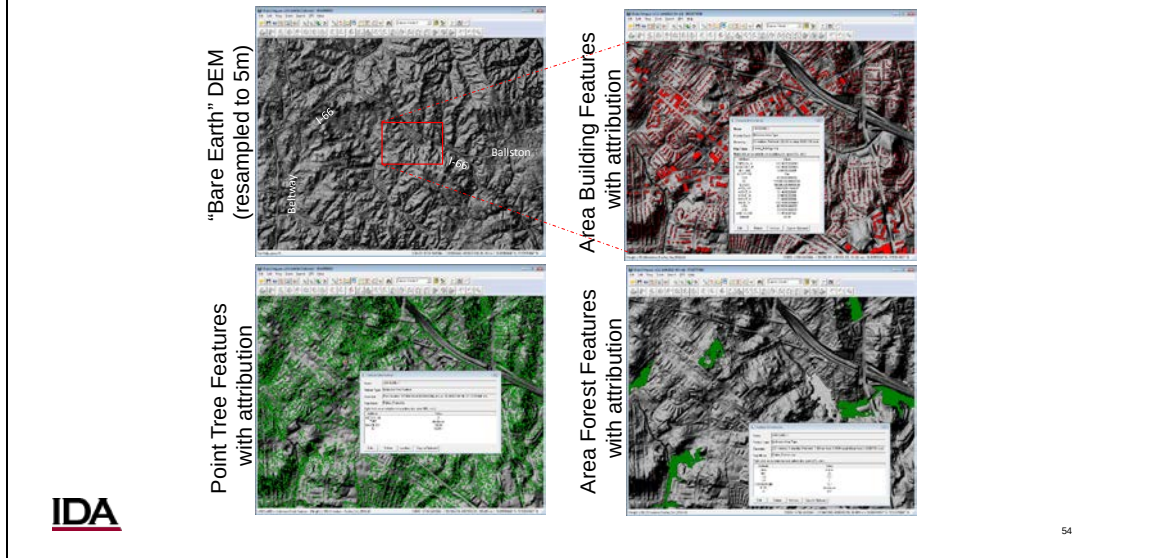
1m DEM in San Francisco from the Homeland Security Infrastructure Program (HSIP)

53

Shaded relief is used to display HSIP DEM over northern San Francisco. This is literally a 1 meter DEM represented in a UTM coordinate projection.

The “reflective surface” Digital Surface Model (DSM) is displayed on the left. The “bare earth” Digital Terrain Model (DTM) is displayed on the right. Individual trees and buildings identified and extracted from point cloud data processing have been used to generate the DTM.

HSIP LIDAR-Extracted Data for Fairfax (VA) Test Site



LIDAR data processing and automated feature extraction has been performed by specialists under NGA geospatial production contracts providing an important demonstration of a large operational program executed by state-of-the-art performers.

In the upper left, a shaded relief image generated from the 1m "bare earth" DEM depicts the "Fairfax Test Site" in northern Virginia extending from Ballston in the east to Tysons Corner in the west. The area outlined in red is depicted in the other three images with feature data shown with color overlays on shaded relief background.

Building footprints are shown in red in the upper right. One of the many area Building features has been selected to display the associated attributes.

Locations of individual point Tree features are seen in green in the lower left image. One feature has been selected and associated attributes are displayed.

In the lower right, area Forest features are depicted in green with a display of the attributes for a selected feature.

Perspective View of Ballston



IDA

55

This screenshot from a real-time 3D viewer provides a perspective view of the Ballston section of the resulting terrain data base. Both the old and new DARPA buildings are highlighted in red.

DEM Recommendations

Level	Post Spacing		Recommendation for the Coterminous United States
	arc-sec	meters	
0	30	~ 1,000	GMTED (30, 15, and 7.5 arc-second)
1	3	~ 90	Down-sample NED 1 arc-second
2	1	~ 30	NED 1 arc-second
3	0.4	~ 12	NED 1/3 arc-second
4	0.11	~ 3	NED 1/9 arc-second
5	n/a	1	HSIP, USGS, USACE, AGC Buckeye



56

I have been asked to make recommendations for DEM over the coterminous United States. While the examples presented here have focused on DEM Levels 2 and 5, I'll extend my suggestions to all six levels of detail.

While there has been no discussion of Level 0 (~ 1 km) DEM here, this is another example of many available data sets from well-know mapping agencies. Today it is easy to recommend the most recent entry, the Global Multi-resolution Terrain Elevation Data (GMTED), a collaborative effort by USGS and NGA.

The previous examples make the case for using NED at Level 2 Level 3 since full coverage is available. Given the lack of a better alternative, down sampling NED 1 arc-sec data is recommended to meet any Level 1 requirement.

While NED 1/9 arc-sec has not been discussed, it is the best Level 4 candidate for regions where it is available.

Level 5 requirements are satisfied by LIDAR-derived DEM. While availability is limited, primary sources include HSIP for 133 urban area, USGS, Corps of Engineers Districts (USACE), and Buckeye coverage from the Army Geospatial Center (AGC).

Wrap-Up

- DEM products are increasingly available
 - Easy to find and simple to download
- All DEM products are not created equal
- Characteristics and quality varies with data source and production method
 - Carto
 - Stereo
 - IFSAR
 - LIDAR



57

Digital Elevation Models are increasingly available, easy to find, and simple to obtain. All DEM products are not created equal. While one tends to focus on just the horizontal post spacing, examples shown here illustrate that data characteristics and quality that vary dramatically depending on the data source and production method.

The earliest production effort relied on vector-to-raster conversion of 1:250,000 contour line by unsophisticated algorithms. While these carto-derived products may be considered primitive to-day, more advanced vector-to-raster algorithms operating on high quality 1:24,000 are performing very successfully to meet national needs.

Great quantities of elevation data have been produced using stereoscopic techniques. As illustrated here, this technology can lead to outstanding products as shown by Range 400 or a product with significant anomalies (e.g., ASTER).

While SRTM pioneered generation of a near-global DEM, IFSAR technology have inherent noise characteristics. Such anomalies have been reduced, but not eliminated, by the airborne NEXTMap system.

LIDAR has revolutionized generation high-resolution DEM and support the first large-scale examples of automated feature extraction of buildings and trees. LIDAR remains constrained to lower altitude, narrow swath width acquisition.

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14. ABSTRACT This IDA-sponsored project had two related objectives: (a) to gain insight into current practice in terrain modeling to predict RF propagation; and (b) to identify opportunities to exploit contemporary geospatial data sources to advance the state-of-the-art in RF propagation modeling. Discussions with technical staff at the Institute for Telecommunication Sciences (ITS) and the Defense Spectrum Organization (DSO) identified that current practice for RF propagation modeling in the coterminous United States has relied on use of elevation data from the Shuttle Radar Topographic Mission (SRTM). SRTM used interferometric synthetic aperture radar (IFSAR) technology with inherent noise characteristics. For the coterminous United States, higher fidelity and higher resolution data derived from aircraft is available as USGS National Elevation Data (NED). Experiments were conducted with the ITS Irregular Terrain Model (ITM) using two resolutions of SRTM terrain and two resolutions of NED terrain for comparison to ITS field measurements. For a 3.5 GHz transmitter located in Boulder, Colorado, a vehicle-mounted receiver had been driven across the Table Mountain plateau near Longmont, Colorado. Inconsistencies in predicted returns at Table Mountain reflected SRTM elevation anomalies. In the future, field measurements taken at multiple frequencies would help to determine where dominant multiple scattering occurs, and this could help inform model improvements A Primer for Digital Elevation Data, based on presentations to ITS and DSO technical staff, is included as an appendix.					
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